INCREASING BYSTANDER AND ENVIRONMENTAL AWARENESS THROUGH HAPTIC FEEDBACK

by

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ABSTRACT

The Chariot System is a bystander and environmental awareness system that uses vibrotactile haptic feedback delivered via a wearable. It was designed with the goal of using a subject's haptic channel to keep them aware of their surroundings thus freeing their visual channel to focus on and enjoy a virtual reality (VR) experience. This work contributes to the space of VR research that aims to keep users aware of the outside world while in VR, an area that typically focuses on using visual notifications but rarely applies haptics. A user study involving 24 participants was conducted comparing the Chariot System to an analogous visual notification system to determine haptic feedback's efficacy of alerting participants to virtual passersby while partaking in two different but common VR tasks, watching a video and playing a VR game. After going through each condition, participants filled out the NASA-TLX and System Usability Scale surveys to gauge their experience with both systems. The survey results as well as their accuracy and response times to notifications were then analyzed to compare the performance of both systems. Our findings show that while reaction time using the visual notifications was faster, participants found the use of the Chariots less mentally taxing and preferred. This work could possibly be expanded upon in the future through the addition of real time sensors and more portable power sources for the wearables such that the VR user could physically move around in the virtual environment and be made aware of them approaching or being approached by oncoming persons or obstructions.

This work is dedicated to the teachers, peers, family, and friends who have supported me throughout my academic career.

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HCI:Human Computer Interaction

VE:Virtual Environment

VR:Virtual Reality

CHAPTER ONE: INTRODUCTION

1.1 Reasoning

In the early stages of the coronavirus pandemic the ISUE lab at UCF was running a user study on distance perception in VR. Part of this study was showing subjects a virtual room, have them identify a target, then removing their sight and having them walk forward until they believed they were at their target. While this thesis is not about the findings of that study, a pattern that arose of people being afraid to walk forward into a space they had previously seen as empty. They had just seen that the real world space in front of them was empty, and shown a virtual environment that was empty, and yet their lack of immediate awareness about the area around them had evoked a fear response. We had tried implementing a virtual boundary in the study that would alert people if they walked too close to and were about to walk into the wall of the room an auditory warning would play. However ,with the tracking being unreliable, several people walk into the wall of the room with only a several hundred dollar, and at the time, state of the art headset to cushion the impact. This is where the driving force for the development of a system to help keep subjects aware of their environment while in VR started.

Early in my graduate school career we were working on a VR game for a class project. The purpose of the project was to implement different interaction techniques and the one being worked on at the time was grabbing virtual objects. An issue would however arise whenever an object would fall into a space whose corresponding real life position was underneath a desk. Bending over to pick up the object would result in the unfortunate and sometimes painful event of slamming my head into the hard desk. Turning on the headsets built-in obstruction detection system that was meant to show objects within a predetermined boundary did work to avoid collisions, but the neon grids or outlines would prove to be distracting and reliable for consistent use. The frustration at this is what would push me to choosing haptics as my solution to solving this problem.

1.2 Why Haptics?

While sight is the primary sense we associate with VR, haptics have long since been part of the field of Human-Computer Interaction as another modality to give users information from whatever machine they are working with. Haptic feedback is classified as any type of feedback that targets the users' sense of touch, be it force, touch, vibration , or even heat[10]. This thesis will focus on vibrotactile feedback, the most common type of haptic feedback people encounter on a daily basis, ranging from the buzzer on their phone to alert them to an incoming message or their gaming controller shaking in reaction to an event in their game.

Haptics were chosen as the main modality of sending information to users for this thesis since the sense of sight can be almost overwhelmed in VR for subjects trying to take in the entirety of the VE while also having a Heads Up Display giving more information. Not alone in this endeavor to use haptics to pass more information along to users other research has turned to haptics as a way to give information has been found in the fields of automated driving, accessibility, and even in the piloting of aircrafts[1,2,16]

1.3 Contributions

In order to test the efficacy of using haptics to convey the positions of nearby passersby and obstacles to a user while in VR, a haptic notification system was developed and tested against a similarly styled visual notification system. Both systems were tested with participants going through two different scenarios in VR, watching a 360 video and playing a video game. For each scenario both systems had their efficacy graded by participants reaction time, missed notifications of passersby, and responses to two surveys gauging participants' difficulties using both systems.

1.4 Reader's Guide

The following content of thesis are as follows.

Chapter 2:Related Works- A review of the work previously done into keeping subjects aware of their environment both while in VR or in scenarios where there visual channel is already preoccupied or inaccessible.

Chapter 3:Hardware/Software Design- The process in which the haptic notification system was designed and the reasonings for the choices put into it's design.

Chapter 4: User Study- The design and procedures of the user study conducted to test the haptic notification systems while used in VR. This study collected qualitative and quantitative data from participants through the use of performance metrics and survey responses.

Chapter 5:Results and Analysis- The quantitative and qualitative measures collected from participants in the user study. The measures are then ran through a battery of statistical testing to find statistically significant differences both between each system as well as between each VR scenario.

Chapter 6:Discussion- The statistical significances found in the previous chapter are discussed and expanded upon to explain their meanings and conclusions that could be drawn from them.

Chapter 7:Future Work- Work for future research is proposed based upon the limitations in this study's design.

Chapter 8:Conclusoin- Concluding thoughts on this work and it's findings are presented.

Appendix A:Surveys-The surveys that were presented to participants.

Appendix B:UCF IRB DOCUMENTATION- IRB approval letter

CHAPTER TWO: RELATED WORK

Modern day head mounted displays(HMDs) all come standard with some way to convey information about the real world to their users while in their VE's. For example, the Meta Quest 2's Guardian system requires users to either draw a virtual boundary using the headset's inside-out tracking or to confirm a basic circular boundary if they intend to be stationary for their time in VR. If the user crosses their virtual boundary the virtual world is no longer rendered and is replaced with a live feed from the HMD's cameras and they are directed back to their predefined boundaries or are asked to redraw it. While an effective strategy of making the user aware of their physical environment, this sudden shift from the VE to the real world and back to the VE breaks the user's presence in the VE. While this work is not focused on the idea of presence in a VE, the maintenance of an adequate level of awareness of the world outside the VE is. Visual aids(such as the aforementioned Meta Quest 2 Guardian and the HTC Vive's play area) are the most direct way to grasp the user's attention and make them aware of their surroundings, but as previously stated they are also distracting from the task at hand. In an effort to search for other, less obtrusive, ways to give users environmental and bystander information, past research has looked into different strategies to keep user's aware of the outside world while in VR.

2.1 Haptic Feedback Devices

Haptic feedback devices have taken on a variety of forms and functionalities since their introduction to the field of HCI in the 70's[11]. They have ranged from the older large mechanical armature pieces that can supply force feedback to the user to the new modern haptic suits such as those developed by Teslasuit that uses electro-tactile stimulation to simulate a variety of sensations across designated zones of the human body. Research into wearable haptic devices in recent years have looked into expanding the sensations that can be supplied to the body ranging from squeezing and stretching sensations via the use of constricting bands and motors to apply tension [15,16]. One of the primary driving forces of wearable haptics is to complement the growing advancements in hand/finger tracking that are implemented in newer VR/AR devices such as in the Meta Quest 3 and Apple Vision Pro.

2.2 Visual Cues as a Modality to Convey Environmental and Bystander Information

While a visual cue can be the most straightforward and easiest to implement type of notification, blending them with the user's specific VE and task can prove to be a challenge. Medieros et al. created several types of visual systems to help promote bystander awareness utilizing both "push" and "pull" type notifications [13]. A "pull" type notification is one that requires an action on the user's part access it's information where a "push" type notification is similar to the ones we encounter on a regular basis where no prompting is required by the user and they appear as they come to the user. A proposed system in this paper that was of interest for this study was known as "color glow" which presented a glow of color on the side of the user's field of vision corresponding to the side of approach of a bystander. User feedback about this proposed system found it to be familiar to users who played many shooting games. The other proposed systems in this study included a traditional minimap overlay on the user's field of view, a set of arrows that pointed to bystander's locations in the real world, as well as implementing a virtual avatar of bystanders when they were close enough to the user. Results of initial testing of their overlays with an action game found that the use of the arrows were most accurate but with some user's reporting it to be hard to understand what it was exactly communicating about the bystander's position.

Von Willich et al.'s implemented visual cues also incorporated the idea of virtual avatars for bystander's near the VR user [21]. They did a user study implementing varying levels of integration for the passerby with the VE, with the lowest level being an overlaid video feed captured by the headset's camera and the highest being a tracked virtual avatar. Results of their user study implementing their systems with a puzzle game showed that the implementation of a 3D render of the passerby resulted in the fastest reaction time as well as it and the virtual avatars had the most accurate findings.

Kudo et al. designed their visual cues with the design aspects of the cues either being situated in the virtual scene or separate from the virtual scene[8]. Like the work done by Medeiros and Willich, they displayed the relative position and orientation of the bystander either as a heads up display element or as an actual part of the virtual scene. Aside from implementing a similar virtual avatar system to the other two works, Kudo implemented a radar heads up display widget that showed not only the relative position of the bystander to the user in VR, but also their orientation. Another heads up display widget they developed functioned similarly to Medeiros' with a generic image of a person, but rather than having the image turn to face the wearer, as the bystander approached the wearer the image would increase in size, opacity, and gain eyes. In order to test the effectiveness of their systems they applied each one to three different VR scenarios, a first person shooting game, a 3d drawing task, and watching a 360 video. Results of their testing found that while the avatar representation of the bystander resulted in the highest accuracy of recognizing bystanders, the radar widget set maintained the user's immersion in VR the best. Looking across the different types of VR scenarios they drew the conclusion that the awareness visualizations should change with the different scenarios, leading to the idea that there is no "one-size fits all" awareness system.

Li et al. focused on communicating bystander intentions to the user while they (the bystander) is at a constant distance from them[10]. This was meant for the use case of someone sitting next to the user in VR for a prolonged period of time. They tested the use of varying representations of the bystander ranging from a generic picture of a person which would rotate the person to show their intention to communicate with the VR user to a full 3D avatar of them that would also rotate. For their study they used a rhythm game to mostly occupy the user's attention and had a researcher play the part of the bystander. They found that there was no significant difference between their baseline (no visual systems in place) and their implemented systems when it comes to the number of missed cues that the bystander wanted to interact. When it came to reaction time, the avatar implementation had the longest time to react since the avatar was located just outside of the user's field of view and required them to actively look away from the game to perceive the bystander's intention.

Mansour et al. did an evaluation study on some of these proposed visual notification systems and introduced the idea of a "reality awareness continuum" that sorts these systems by how much information they give to the user[12]. As an example, a plain text notification of "someone is watching you" gives the least amount of information, the avatar and radar approaches from works such as in Li and Kudo's give a middling amount of information, and a live video of the real world would give the most information. Mansour's work was looking at the productivity of a user in VR while using these different systems and found no significant differences in user productivity regardless of the system used.

2.3 Haptic Feedback as a Modality to Convey Environmental Information

Work done to utilize haptic feedback as a tool to give visually preoccupied users environmental information is not just found in the VR and HCI fields but also in other fields such as in workplace risk management, the automotive industry, and accessibility . Yusof et al. 2023 developed a system for use in automated vehicles to notify the passengers of upcoming turns without disrupting whatever task they are completing while riding[22]. They elected to use force and vibrotactile feedback so as to keep the riders visual focus on the task at hand. Figure one shows the typical use case of the system which functioned by alerting the passenger of an upcoming turn by pulsing the haptic motors on their wrists. After the notification was sent, force was applied to the passenger's back turn them to compensate for the centrifugal forces that would normally disturb the passengers. A user study conducted to test how the system effected the riders mental loads and situational awareness through a reading comprehension test about the text they were presented with the system in use. The proposed system was compared against a visual warning system that would be displayed next to the text. Study findings showed that the haptic display required a lower mental load than the visual display for maintaining situational awareness. The reading comprehension scores interestingly remained the same from the control test conditions which could be interpreted to mean that for a lower mental load, a rider's comprehension of the text could be the comparable along with an increased amount of situational awareness.

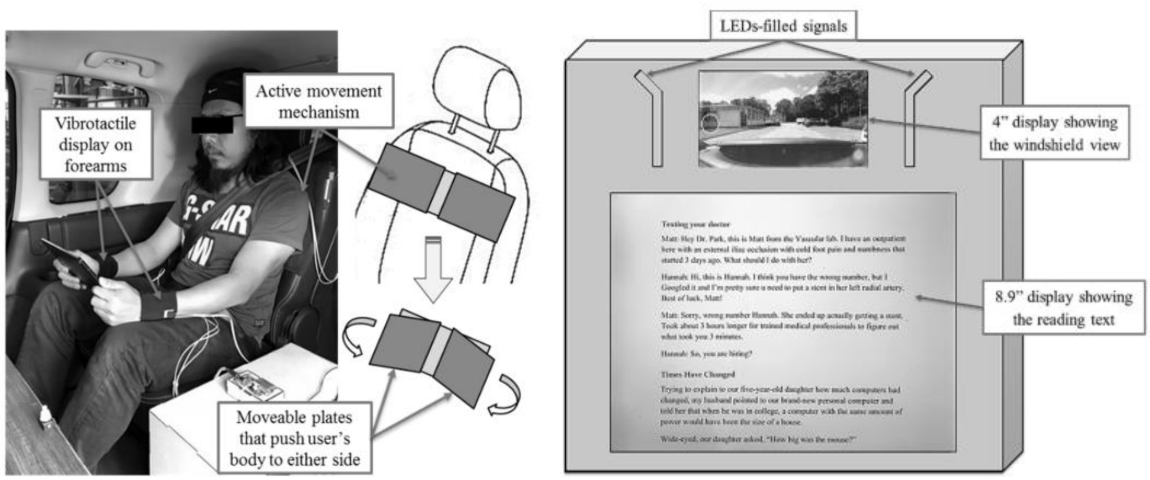

Figure 1.The Haptic and Visual Displays used in Yusof et al. 2023[22].

Khaliq et al. 2021 attempted to apply haptics to aid users navigating a maze by using various combinations of visual ,audio, and vibrotactile feedback with the goal of creating a system to aid for when visual acuity is degraded or lost[7]. Their proposed system was a band worn on the trunk of the body outfitted with several tactors that used the funneling sensory illusion to create the feeling of a point moving continuously on the user. The funnel illusion describes the phenomena where alternating stimulation between two points on the body leads to a third perceived place of stimulation between the original two. The illusion was leveraged in this study by modulating each actuator's intensity with time such that the perceived point seems to move. A user study was conducted that consisted of navigating through a maze with various combinations of the visual, audio ,and/or haptic cues directing users through a maze while in the presence of audio/visual distractions. The different sensory modalities and their effectiveness were based on users' reaction time to their given instructions as well as task completion of the maze which was broken down into a scale from 0 to 6 given by 6 predetermined checkpoints in the maze.

Statistical significance was found between task completion and the sensory inputs along with stronger significance in the cases where distractions were present. It was found that when in the presence of distractions, the audio/ visual cues had improved performance when also paired with the haptic feedback. Significance was also found between the reaction time of users to directions and task completion. Reaction times were reported to be highest on average in all cases where the haptic feedback was present when compared against the other modalities.

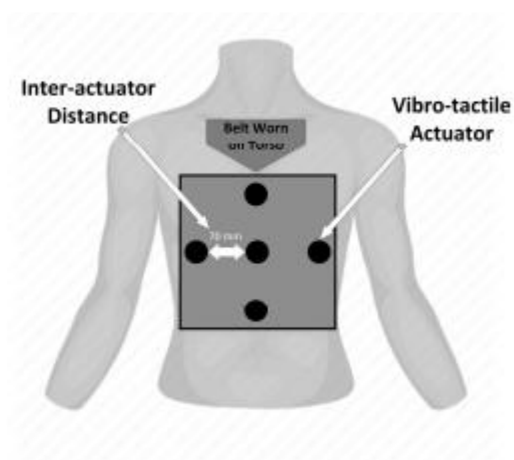

Figure 2.A mockup drawing of the haptic belt developed by Khaliq et al. 2021 [7].

George et al. 2020 looked into conveying information about a user's position relative to unseen boundaries while in VE's[4]. Their system consisted solely of the provided HMD's along with noise canceling headphones. When using their system, if a user's handheld controllers were within a preset boundary to the invisible boundaries they would receive either an audio and haptic cue from their headphones or controllers respectively or the previously invisible barrier would be visually rendered. George's system was developed to not need an interruption of the simulation to redraw boundaries to allow for a dynamically changing bounding area. The user study designed to test these boundaries was based around the children's game "The Floor is Lava" which has users move quickly within the play area in an effort to push participants closer to the digital boundaries. Participants were divided into three groups, audio/haptic cues and blindfolded, audio/haptic cues, and visual cues. Participants in all three groups are given a training phase to make sure they know how the games with the blind folded participants are given an additional training phase to learn the boundaries. After completion of the three rounds, two rounds are played with an obstruction in the play area to create a change in the user's play area. The data reported in the study featured the amount of times a user went past their respective boundary(breaches) per group as well as the extent and time spent outside the boundary. Statistical significance was found between study groups when it came to the number of breaches, part of which can be inferred from the observed behavior of users during the study. Some users were observed to be holding their arms out while in motion to get an earlier warning of a boundary before their HMD passed through the barrier since the haptic and audio cues for the controllers and headset were given independent of each other. On average the users that had the blindfolded condition had fewer controller breaches than those without it. The group with the visible boundary reported the fewest controller and HMD breaches. Survey results found that the invisible boundary system was found to be more taxing on the user, but users who did not have the training round found it to be significantly less physically taxing.

Valkov et al. took a different approach in the placement of their haptics, placing their tactors on the portion of the HMD that contacts the wearer's face and attaching time of flight sensors to the front of the HMD[20]. This work tested various transfer functions of the vibrotactile sensations in relation to the distance of between the wearer and the detected obstacle. To take movement into account they added dynamically changing distance intervals based on the relative speed between the wearer and the obstruction. Simulating the sensor inputs they tested their different signal mapping functions with a user study that had participants walk towards a virtual wall. No significance with the different signal mapping functions were found when the dynamically changing distance intervals were introduced but even without the distance intervals no significance was found between the mapping functions.

2.4 Haptic Feedback as a Modality to Convey Situational Information

Vibrotactile haptic feedback being used to give situational information is a common application when we look at their implementation in smart phones and game controllers where they are most used with. Beyond the basic vibrotactile feedback Pohl et al. 2017 tried to implement pneumatic compression to assist with mobile notifications[16]. The basis of their thinking was that current mobile phone haptic feedback, while effective, can also lack the ability to convey varying degrees of importance of a given notification. Their solution was a pneumatic bladder system that would allow for different amounts of pressure to be applied to the wrist. This would allow for more varying intensity of notifications to match with different types of mobile phone notifications.

In a study to compare their proposed compression feedback against traditional methods users were told to play a memory game on a desktop with a phone in their pocket and a pneumatic wristband fitted to have both compression and vibration capabilities. The only statistically significant difference in user performance was their response time to notifications, with compression feedback taking a longer time for the users to acknowledge the phone while playing the game.

Figure 3.The compressive feedback device designed by Pohl et al. 2016[16].

Schnelle-Walka et al. 2016 worked on using computer vision system to determine a person's body posture as a measure of how much they want to socialize with a user who is visually impaired[17]. This information is then turned into either an audio or tactile signal which is delivered via a mobile phone to the user. Testing with blind participants found users preferred the tactile feedback for uses in outdoor scenarios such as on the street to leave their auditory channels open to the rest of the world.

Fink et al. 2023 in worked on creating a haptic display to improve situational awareness in self-driving cars similar to the study done by Yusof et al. 2023 but instead of the intended user being in the back seat of the automated car, the system is intended for the passenger in the driver's seat of the car[2]. They employed the use of an ultrasonic transducer array to create tactile feedback on the palm of users ,drawing out symbolic representations of intersections of roads. Preliminary studies found that users' performance was statistically the same as when compared to the current standard of tactile depiction of road intersections which is the printing of embossed patterns on paper. Time to recognize the patterns however were statistically longer with the ultrasonic interface but on the order of 10's of seconds when most stops at intersections taking much longer to resolve.

Figure 4.The ultrasonic haptic device created by Fink et al.2023 [2].

Wolf et al. 2018 tried their approach at haptics based situational awareness by moving the sensations off the hands and abdomen and instead placed them on the sides of users' heads[18]. The group studied the ability of users to identify the source, pattern, and duration of the haptic stimuli on the sides of their head both with no other stimuli present and while playing a mobile game. The use of the mobile game was to provide a constant visual and cognitive stream of information like they would while traveling. Study results found that users could consistently identify the patterns and location of the haptic sensations placed on their head. The introduction of distractions, the mobile game, to the user did not significantly increase the perceived mental workload of the user.

Figure 5.The head based haptic system developed by Wolf et al. 2018 [18].

A secondary study was done to measure the device's ability to convey situational awareness while walking at varying paces, ranging from staying stationary to walking at a brisk pace. The position of the hazards were communicated to the user via the location of the stimuli on the head and the distance of the hazard was denoted by the amplitude and shape of the haptic signal. Distant hazards were signified using sinusoidal waves and as the user approached the hazard the signal became a higher amplitude square wave. The implementation of an “update” signal was done to give the user a way to break up the haptic signals for each detected hazard. Findings of the study showed that despite cognitive workload increasing as the users’ physical exertion level increased, situational awareness remained constant.

Fellah et al. 2019 looked into haptics applications into fighter jet cockpits for[2]. Given the multiple tasks a pilot has to do concurrently while in flight or in a combat scenario, the work was done to see if some of the information that is presented to pilots through the visual channel could be offloaded to the pilots haptic channel instead in the hopes of reducing mental workload.

Interviews with a pilot from a previous study found that important information that should be relayed to pilots via a non-visual channel is their climb angle and turn rate. Flight path information was encoded into haptic signals and were divided by the regions of the pilots body that are stimulated, needing a turn to the left or right vibrates the left or right sides of the abdomen respectively. Similarly, needing to climb or decline in altitude would vibrate the pilots back or abdomen respectively with a cruising altitude being represented by both sides being stimulated simultaneously. Tactors located in each region of the body had a predetermined set of angles between them, with each turn and bank angle having a corresponding tactor meant to convey how much to turn or climb the plane.

The system was tested in three studies, two being with licensed pilots given a two week period to learn the interface and then using the system on a test flight with a predetermined flight path and maneuvers, and one with university aged participants . One flight used only the visual channel used to convey flight data and another flight was done with the visual and haptic channels giving flight information. After completing both flights, the pilots were given a questionnaire and post task interview. Testing on the questionnaire results and flight data found that there was a significant improvement in flight pattern accuracy with the haptic and visual channel being used when compared to using only the visual channel. The second study was to evaluate the system in a situation where the user is spatially disoriented. This was done by spinning users in a chair for a prolonged period of time and testing if they could accurately perceive the interfaces instructions. Users after being spun were found to be unable to read or locate the flight instruments in the room but all were able to immediately perceive the haptic interface. The last study was similar to the first where the functionality and usability of the interface was tested by again having three test pilots take the interface for a flight and then filling out a questionnaire. Qualitative analysis of the pilots answers found that they had a harder time differentiating between the vertical feedbacks as opposed to the horizontal feedbacks; as well as indicating that while the haptic system was easily understood a longer training period would be required for the different patterns to be fully understood.

Fang et al. looked at the applications of vibrotactile haptics and auditory feedback for use in construction sites[1]. They created a head mounted haptic and audio display that responded to whenever a user was within a predefined radius of a typical hazard on a construction site. To test their head mounted display, a VR user study was ran with participants completing simplified versions of construction tasks. These tasks required the participants to travel around the VE using teleportation and if they teleported too close to a hazard, they would receive either an auditory,haptic, or an auditory plus haptic alert to make them aware of the danger. Response times to each of the alerts were measured along with participants' subjective emotional responses to the alerts via a survey. Statistical significance was found between the reaction times of the audio alert and the vibrotactile alert as well as between the audio alert and the audio with vibrotactile alert, both alerts using vibrotactile feedback having the faster of the two reaction times. The emotional survey responses found that participants found the audio plus vibrotactile feedback and the vibrotactile feedback to be more upsetting than just the audio alone, which in terms of a warning system can be seen as a positive factor.

CHAPTER THREE: HARDWARE/SOFTWARE DESIGN PROCESS

The design for the haptic wristbands(from here on referred to as Chariots) was built around the typically unused real estate of the wrist on a VR user's body. This chapter will go in detail into the several factors and limitations that lead to their final design and choice of placement.

3.1 Hardware Design Process and Basis

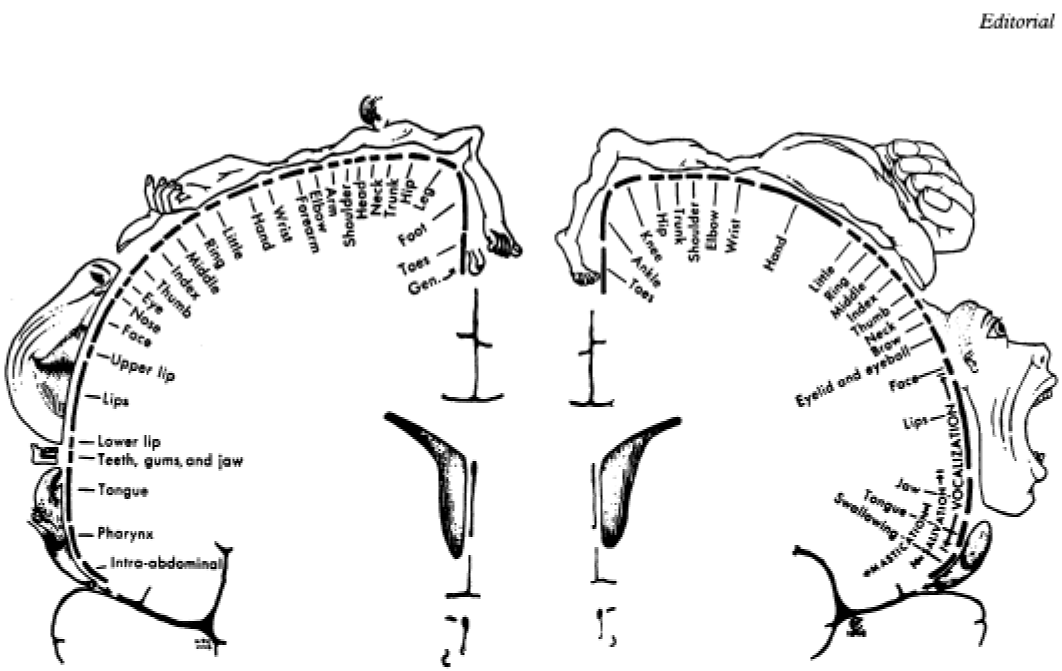

Figure 6.The homunculus model of human sensory experiences(figure sourced from Schott,1993)[19].

The homunculus is a model of the human body used in the field of HCI to illustrate the distribution of nerve endings on the human body, with the largest concentration of them being on the face and hands. This makes logical sense of course when you consider that these are the parts of the body which we use to interact with our environment. While placing the haptic motors on the face or hands of the user would almost certainly make the haptic sensations more noticeable than on the wrists, these places in the Chariots use case are preoccupied by the VR headset and its corresponding controllers. The wrist placement of the Chariots also makes them forward compatible with improvement of VR headsets as they move towards the use of hand gestures and hand tracking for interactions as changing the hands features or weighing them down with electronics would obstruct tracking or limit the gestures a user could perform. The feet, while also having a high density of nerve endings as compared to the rest of the available real estate for the system, would prove to be an inadequate position for the system due to another design factor of the Chariot system, ergonomics.

Wearable technology at the time of this study's writing has a focus on users' arms and head, immediate examples of this being the prevalence of smart watches,rings,and glasses. An aspect all of these items have in common is their ergonomic design which is the ease in which users can don and doff them at their own discretion. Placing the Chariots on a user's feet or ankle area would at best require them to bend down to place the Chariots around their ankles or at worst require them to remove their shoes to place the system then place them back on. In addition to the several steps needed to place the system on their feet or ankles, most users are not accustomed to having electronics placed on that area of their body. This line of thinking can be further extended to include other parts of the body, including the upper legs, torso, and neck of the user.

With the placement on the user's body narrowed down to the wrist, the next aspect that needed to be decided was the number of haptic motors to use. While having as many haptic tactors as can fit around the wrist sounds like a good idea, there is a point in which adding more tactors leads to diminishing returns. The two-point threshold refers to the minimum amount of space required between two points on the human body to be stimulated and perceived as two distinct sensations.

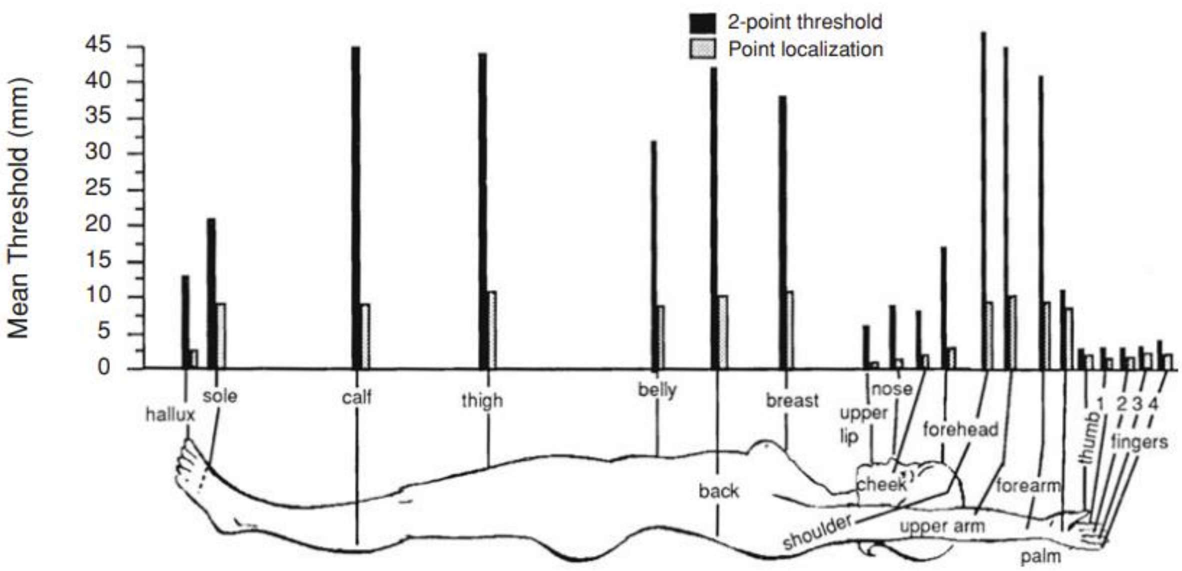

Figure 7.The mean two-point threshold for different locations on the body (sourced from Lederman et al. 2009) [9].

As shown in the previous figure the mean two-point threshold for the forearm area is around 3.5 cm, meaning on average any tactors placed closer than that would not be immediately recognized as two separate points on the wrist. A compounding factor in addition to this threshold is the variability of wrist size within the human population, a person with smaller wrists will have less space for tactors than a person with a larger wrist size. To make things as consistent as possible between users three tactors were chosen as the optimal number of tactors for this study's purpose.

With the placement and number of tactors solidified, the last choice to be made about the haptics of the system would be the type of motors used. While all vibrotactile motors seek to serve the same purpose, creating vibrations, the way they go about it varies between motors. Gaming controllers in the past used what are known as Eccentric Rotating Mass (ERM) motors to create haptic feedback. As their name suggests, these motors achieve vibrations by rotating a piece of metal around an off center axis which would rock the body of the motor left unattached to a housing. While very effective at creating vibrotactile feedback, the downside in the eyes of this study of using ERM motors was the space they required to operate. The mass being rotated by these motors and thus their torque were very low, meaning that even the lightest amount of resistance against the mass's rotation would stop their movement. This was found by early prototypes of the Chariots which held these motors directly against the skin by an elastic sweatband. Quite often the rotating mass would get caught by stray strands of the sweatband or if the motor was pressed too tightly against the skin of the wearer they would stop rotating, resulting in inconsistent and unreliable sensations being produced. The solution to this problem was another kind of haptic motor. Linear Resonant Actuators are a type of haptic tactor that utilize magnetic fields and springs to move a mass and create vibrations. The housings needed for these tactors are extremely thin and are what are commonly used today in devices that require haptics but also need a slimmer physical profile.

The process of choosing how to power and control the haptics of the chariot system was just as in-depth as choosing the haptics themselves. To create as seamless of a user experience as possible for people of all VR levels of experience, an important factor for the microcontroller that would be handling the haptic motors would be that it is capable of wireless communication; either through a local Wi-fi connection or through bluetooth. While initially looking at members of the Arduino family of microcontrollers several issues arose, ranging from the larger size of some boards that made them poor choices for a wearable use case or the lack of wireless communication capabilities. While there were some arduino boards that did fit this study's size constraints and had wireless communication, they sadly lacked easy compatibility with the game software used to run the VR simulation. The solution to this problem was a generic esp-wroom-32 dev board, which was thankfully within this study's size constraints, capable of wireless communication, as well as compatible with the VR game software.

Getting stable and reliable power to the microcontrollers presented it's own unique challenge, deciding whether to power both chariots off a common power source or to let each unit have their own. Each scenario carried its own pro's and cons. Sharing a common power source would save time and resources which could be spent working on other aspects of the study, but with the caveat that if the power cables connecting the chariots to the power source could restrict the user's movement. Having individual power sources for each chariot would mean that the user's movements wouldn't be hampered by any power cables, but this would also mean that additional time and resources would have to be used to design and build the power sources as well as possible ergonomic issues arising from strapping more electronics to the users' arms. Taking all these possibilities into account it was decided that a shared power source for the chariots would be implemented and to ensure that the users' arm movements wouldn't be impacted sufficiently long power cables would be used.

3.2 Software Design

The software aspect of the Chariots while simple on the surface was designed with the intent of recreating realistic scenarios for when a user may be needed to made of aware of passerby or intrusions of their personal space while in VR. Communication between the Unity game engine and the Chariot's microcontrollers were made possible through the use of the Uduino Unity plugin that has built in scripts to facilitate wireless communication over wifi as long as the machine running the VR experience and the controllers are on the same network.

For replicability of the study and the safety of the user the notifications that the user receives from the chariots of passerby approaching them were only simulated, as missing a notification could mean a collision and possibly injury to the researcher and/or the user. The notifications the user's received were set at predetermined intervals of varying length to closely replicate the unpredictable timing of passerby entering the user's personal space while in shared spaces such as classrooms, research labs, or out in public. During the study, when one of the intervals elapses one of the six tactors of the system activates to notify the user to a passerby. The radial nature of the wrist means that when the wrist bands are worn there is one tactor facing the front, side, and behind of the wearer, thus when activated the user will feel the vibrations coming from that direction. This was done to simulate the system detecting passerby approaching from nearly all angles of the user with the exception of from above or from somehow originating from within the user, both of which are highly unlikely to occur in most use cases for the system.

3.3 Final System Design

The final design of the Chariots consists of an ESP-WROOM-32 affixed to a leather wristband using fishing line looped through mounting holes that came pre cut into the ESP's circuit board. This was done to affix the boards to the wristband securely enough as to not fall off but also to give the boards a little bit of play so that they can adapt to curvatures of different users' wrists. When worn properly the ESP would sit on the dorsal side of the user's wrists with its USB port facing the user.

On the underside of the leather wristband is where the LRA haptic tactors are located at equidistant intervals of 1.5 in within the area that is not obstructed by the wristband's velcro straps when it is closed on it's smallest size. The tactors are held in place on the underside by a single layer of duct tape as to not dampen and spread out their vibrations with their wires being fed through holes that were punched into the leather. To reduce the number of wire protruding from the wristbands, the tactors' ground wires are all soldered together to a common wire which is connected to the grounding pin of the ESP. Each of the tactors' live wires were extended so that they could reach their respective locations and are soldered directly to their respective pins on the ESP.

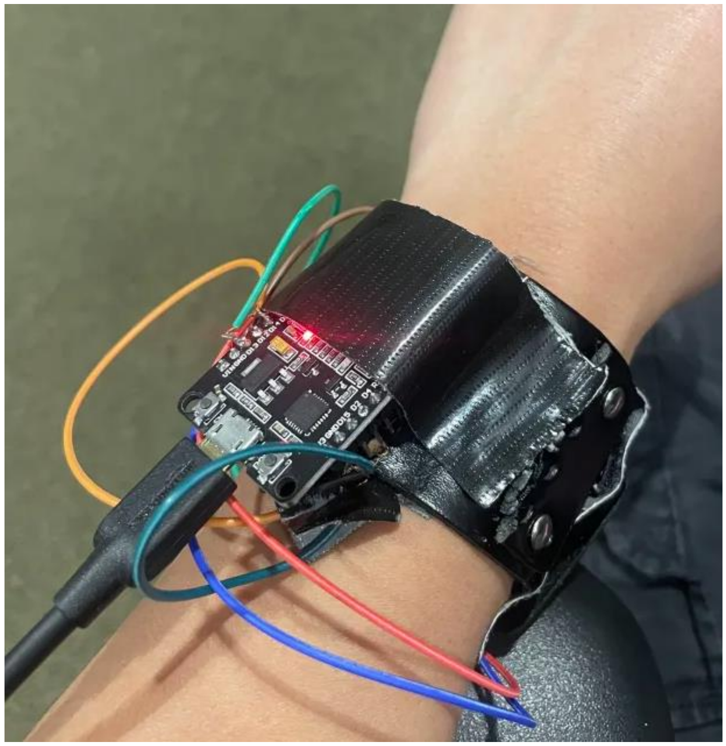

Figure 8.The final design of the Chariot System.

CHAPTER FOUR: USER STUDY

4.1 Experimental Design

A user study was conducted to test the efficacy of the Chariot system when used while experiencing two different types of VR media, a VR game and a VR video. These two types of experiences were chosen for two reasons, they both broadly encapsulate the types of VR experiences users can be expected to partake in while in a shared space; as well as accounting for two distinct levels of interaction with the VE and thus distraction away from the outside world. Moving forward, these two levels of interaction will be referred to as the “Passive case” referring to the VR video in which the only action intended on the user’s part is to watch the video, and the “Active case” referring to the VR game which conversely to the Passive case requires the user to be doing some action in response to the VE. In order to have something to compare the Chariots performance against, a rudimentary visual notification system(VNS) was created in parallel with the Chariots to act as the control case. This then gives us our 4 cases which lead us to 4 test conditions(Chariot system with the Passive case,Chariot System with the Active case,VNS with Passive case,and VNS with the Active case). A within-subject user study was conducted with a sample size of n=24, participants being gathered from the UCF student body. In order to be in the study, subjects had to be in well enough physical health to play the VR game which only involved the movement of the arms, were 18 years of age or older at the time of study,had 20/20 vision or corrected to normal vision through the use of glasses or contacts, and no history of cybersickness. After experiencing each test condition the subjects would complete the NASA-TLX and the System Usability Scale surveys in order to gauge their thoughts on the use of both systems. At the end of the study the subjects would be compensated for their time by being given $5.

Figure 9.A subject in VR wearing the Chariots.

The data that would be analyzed from subjects were their responses to the both surveys as well as task performance metrics from the test conditions they experienced during their participation in the study. The task performance metrics for the Chariots and VNS are the reaction time to the notifications presented to the subjects which was denoted by the subject pressing a button on the VR controllers that they would be holding during the test condition. The order in which users experienced each condition was randomized to prevent the learning effect from impacting the evaluation of the systems being tested. The timing of simulated passerby varied between conditions but were uniform across all users to maintain consistency in the case of the chance that the video/game's contents' effect on the noticeability of the notifications changed with time.

4.2 Apparatus and Materials

This study was conducted using a Meta Quest 2 and touch controllers as the studies VR headset. The scenes where the subject would watch the VR video and play the VR game were built in the Unity game engine using version 2022.3.7f1. The headset would be connected to the laptop running the VR scenes via a USB type-C to USC type A link cable. The laptop running the scenes was equipped with an Nvidia GeForce RTX 3050 GPU(16GB of RAM) and an AMD Ryzen 7 6800 CPU.

If the user would experience a test condition using the Chariots they would be instructed to wear them such that the ESP-32 on the wristband would be on the dorsal side of their wrist with the usb connector pointing towards them before putting on the headset.

4.3 Visual Notification System(VNS)

In order to draw some conclusions about the Chariots' efficacy at notifying subjects of passerby a second system would need to be created in order to have something to compare the Chariots against. The Visual Notification System(VNS) was designed after previous works done in the field of bystander awareness that tested visual interfaces for subjects in VR [10,12,13] . The system presented in Seatmate and the overlay elements presented in proxemics can be considered push notifications means they require no action on the part of the subject to be seen and given this systems use case of shared spaces with the interval between passerby being random these seemed the most appropriate to model this study's VNS after. Drawing from these studies,they both kept their visual elements to the side or periphery of the subject's field of view, so the visual elements for VNS would also be relegated to that region. Medeiro's et al. presented an overlay element known as "color glow" which as the name suggests presented a glow of color on the side of the subject's vision which changed in hue the closer the passerby was to the subject at the time of notification[13]. Given that the Chariots in their current state do not present this type of information, in order to keep the systems as analogous as possible this feature was left out of the VNS.

In practice, the VNS functions as follows. Similar to the Chariots, each notification is presented on either the left or right side of the subject's field of view at set intervals that change between each test condition in case of the chance that whatever is being viewed may have an effect on how well the notification can be perceived. The notifications of passerby are presented as solid red bars which take up the periphery of the participants field of view.

4.4 Procedure

This study was designed as a 2(Chariots vs VNS;within subject) x 2(Active case vs Passive case;within subject) within-subject study where all participants experienced all the conditions and evaluated the Chariots and VNS performances after each condition. For the Passive case all the subject had to do was sit and watch a 360 video in VR and whenever they perceived a notification they had to press down on the joystick button of their VR controller of the corresponding side where they saw the notification. The Active case called for the same as well as to have the subject to attack different fruit that would be approaching them at varying speeds using either their virtual sword or gun,the sword only required the model of the sword and the fruit to collide for it to count as an attack and the gun required pressing down on the trigger button as well as aiming at the fruit for it to count as an attack. The study took place on UCF campus in the ISUE lab located in the L3 Harris Engineering Center room 208 with the principal investigator(PI) present and the procedure was as follows.

1. The subject was handed a consent form that explained the intent and expected content of the study and was asked to sign and date the form to show they understand what would be asked of them.

2. The PI would then reiterate the content of the consent form verbally to the subject and clarify any questions the subject may have.

3. The subject would complete a demographics survey to collect their age and gender identity, as well as ensure they have the adequate vision,are in good health, and have no history of cybersickness.

4. The PI would explain to the subject how to note down when they noticed a notification from either the VNS or the Chariots.

5. The subject would then be provided with the VR headset and controllers(Meta Quest 2 and Touch Controllers) and instructed on how to tighten or loosen the headset straps or adjust interpupillary distance between the lenses inside the headset as needed by the subject.

6. If the following test condition utilized the Chariot Wristbands, the user would be instructed and/or assisted putting them on correctly and supplying power to them via a USB cable that would plugged into them.

7. The subject would be put through one of the four test conditions of the study for a period of ten minutes during which they experienced five passerby notifications split between the left and right side and in the Chariots case further split between six tactors.

8. The PI would explain the intent of the survey and how to appropriately answer the survey.

9. After ten minutes had elapsed the subject would remove the VR headset with the assistance of the PI if needed and complete the Post-VR survey.

10. The PI would offer the subject a break they needed it and asked if they would like to continue.

11. Procedures five through eight would be repeated for the remaining three test conditions.

12. Once all four test conditions were completed by the subject the PI would ask them what they thought about each system and record any feedback of note.

13. All equipment would be collected back from the subject by the PI.

14. The subject would be given $5 then told they are free to leave the lab.

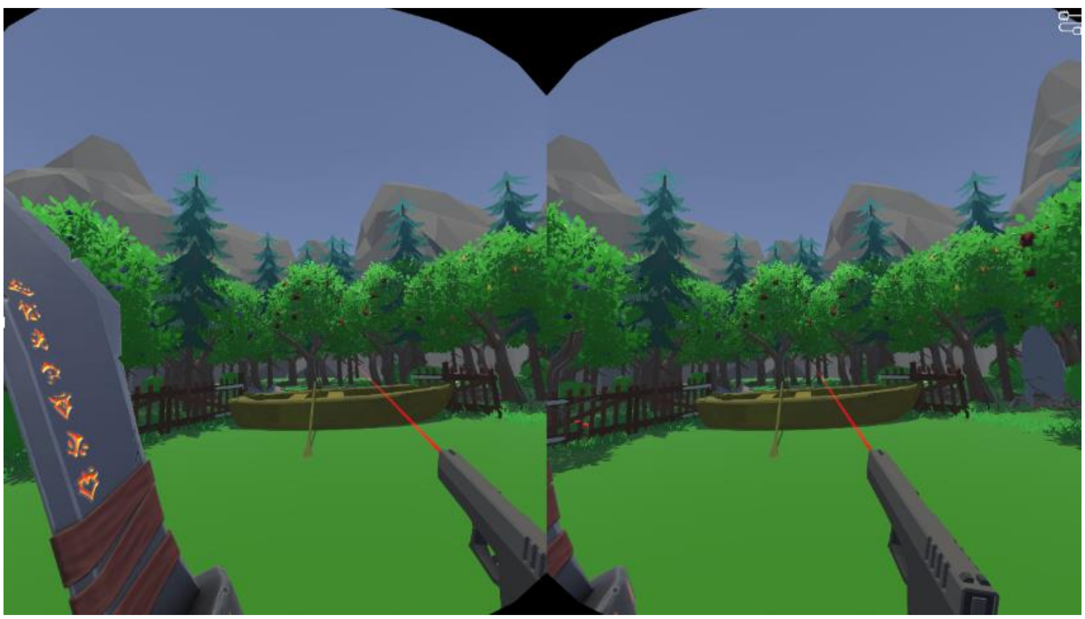

Figure 10.A screenshot of the active case gameplay.

Figure 11.A screen shot of the passive case with the VNS notifying the subject of a passerby on the left.

CHAPTER FIVE: RESULTS AND ANALYSIS

5.1 Demographic Survey

Before participating in the VR portion of the user study, participants were asked to fill out a demographics survey to confirm their eligibility for the study. Our study population consisted of 24 participants collected from the local university and area population (14 male participants,7 female participants, and 3 participants who identified outside the gender binary).

5.2 Performance metrics

As previously stated the performance metrics collected for the Chariot system and VNS were participant's reaction time to the notifications they received as well as the participant's missed notifications.

A notification is considered missed if a user either doesn't respond to the notification or if their reaction to it comes more than 10 seconds after the notification. This 10 second cut off was determined since for the use case of these systems a missed notification would mean a collision with a bystander or an obstruction in the participant's environment which at a minimum is a minor inconvenience or at worst catastrophic in nature. In the instance a response was logged after the 10 second cut off but before the following notification is presented to the user, this is not considered a miss but a "false positive". False positives were only present in less than a handful of participants data and were excluded when calculating any participant's performance

Reaction time in this instance is defined as the duration of time between the start of the notification from either system and when the participant presses the button on the VR controller to acknowledge they noticed it.

5.2.1 Missed Notifications

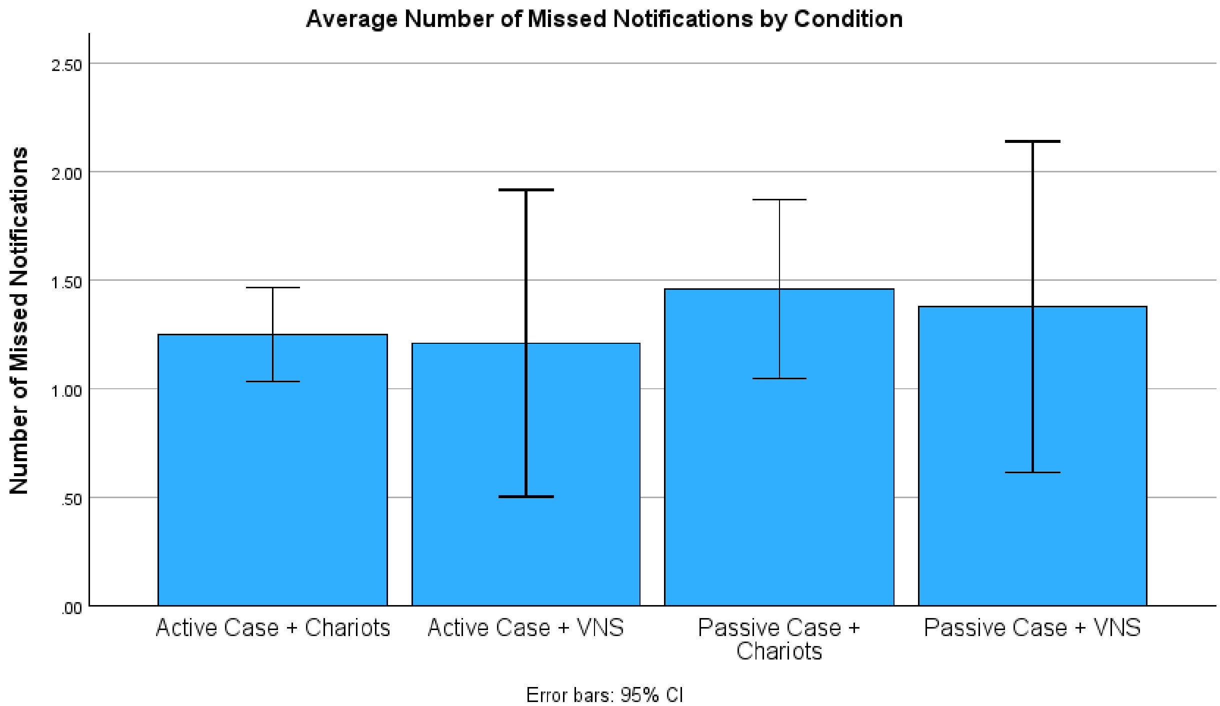

Figure 12.Average number of missed notifications by condition.

Table 1.The descriptive statistics for the collected missed notification data.

Test Condition	Mean Missed Notifications(out of 5)	Std deviation	N
All responses	1.3229	1.387	96
Active case + Chariot	1.25	.531	24
Passive case + Chariot	1.4583	1.02	24
Active case + Visual	1.2083	1.74	24
Passive case+ Visual	1.3750	1.744	24

Shown above are the mean number of missed notifications for all four test conditions as well as the aggregate mean for all reported responses. While at a glance it appears that the participant's performance were mostly equivalent across all four conditions, before any conclusions could be drawn we needed to test for significance. In order to determine what statistical analysis could be completed on the data we ran the Shapiro-Wilk test for normality with a significance value of $p<0.05$ on the aggregate data. 0.05 will be the level of significance required for the rest of the study.

Table 2 Results of the Shapiro-Wilk Test for Normality on the collected number of misses.

Shapiro-Wilk Test for Normality			
	statistic	Degrees of freedom	Significance (p)
All responses	.725	96	<0.0001

After applying the normality test we found that the data was not normally distributed so we applied the Friedman statistical test to see if there were any statistically significant differences between the number of misses between each test condition.

Table 3.Results of Friedman on the collected number of misses.

N	24
CHI-SQUARE	7.810
df	3
Asymp. Significance	0.05

With the results of Friedman being at the required level of significance, we wanted to see if there were any statistically significant differences between each test conditions data. This was accomplished by performing the Wilcoxon-Signed Rank Test with a Holm's sequential bonferroni adjust to account for Type-I errors in the data.[5]

Table 4.Results of the Wilcoxon-Signed Rank Test.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Passive Case + VNS	-0.914	0.361	0.008333333	Not Significant
Passive Case + Chariots	Active Case + Chariots	-0.794	0.427	0.01	Not Significant
Passive Case + VNS	Active Case + VNS	-0.721	0.471	0.0125	Not Significant
Passive Case + Chariots	Active Case + VNS	-0.617	0.537	0.016666667	Not Significant
Active Case + VNS	Active Case + Chariots	-0.437	0.662	0.025	Not Significant

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + VNS	Active Case + Chariots	-0.045	0.964	0.05	Not Significant

Based upon the findings of the Wilcoxon-Signed Rank test we found that there was no statistically significant difference in the number of misses when comparing each test conditions data set against each other. What this could be translated into for real-world applications means that a user using either the Chariots or VNS while in a public setting are equally as likely to either notice or not notice a passerby walking near them.

5.2.2 Reaction Time

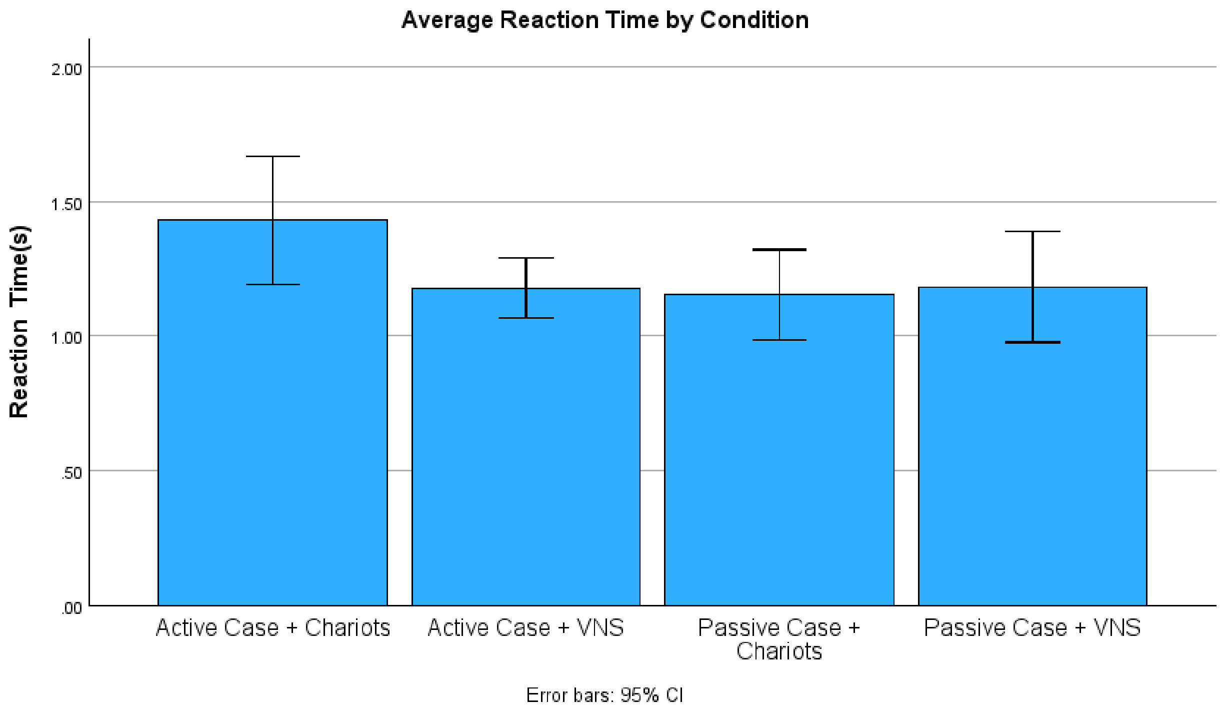

Figure 13.Average reaction rime by condition.

Table 5.The descriptive statistics for the collected reaction time data.

Test Condition	Mean Reaction Time (s)	Std deviation	N
All responses	1.273	0.418	89
Active case + Chariot	1.43	0.487	19
Passive case + Chariot	1.152	0.348	19
Active case + Visual	1.1778	0.231	19
Passive case+ Visual	1.1838	0.427	19

Above is the mean reaction time across all four test conditions as well as the reaction time for each individual test condition. The reasoning for the discrepancy between the number of samples in this table when compared to the previous tables and within the table itself is due to the fact that for several users they missed all five notifications for certain conditions. The differences in sample size for each data set were handled by the software that was running the statistical analysis.

Similar to the missed notification data, we ran the data sets through a normality test to determine the types of statistical analysis that would be appropriate for this data with the results shown in the following table.

Table 6.Results of the Shapiro-Wilk Test for Normality on the reaction time data.

Shapiro-Wilk Test for Normality			
	statistic	Degrees of freedom	Significance (p)
All responses	.725	96	<0.001

With the reaction time data not being normally distributed, we then ran Friedman on the collected data to see if there was significance within the data.

Table 7.Results of the Friedman test on the reaction time data.

N	19
CHI-square	13.295
df	3
Asymp. Significance	0.004

Table 8.Results of the Wilcoxon-Signed Rank Test on the reaction time data.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + Chariots	-3.224	0.001	0.008333	Significant
Active Case + VNS	Active Case + Chariots	-2.711	0.007	0.01	Significant
Passive Case + VNS	Active Case + Chariots	-2.576	0.01	0.013	Significant
Passive Case + Chariots	Active Case + VNS	-0.574	0.566	0.167	Not Significant
Passive Case + VNS	Active Case + VNS	-0.483	0.629	0.025	Not Significant
Passive Case + Chariots	Passive Case + VNS	-0.224	0.823	0.05	Not Significant

Based on the results of the Wilcoxon-Signed Rank Test there is a significant difference in the time it takes for a participant to react to a passerby when using either the VNS or Chariot system. More specifically we can see that while there is no significant difference in the reaction times for the VNS and Chariots when in the passive case, there is a significant difference between the systems in the active case. We can interpret this to mean that while participants are focusing on performing a task they are likely to respond faster when using the VNS when compared to the Chariots. The other significances found show that participants responded faster with the Chariots when in the passive case and that participants responded faster to notifications in passive case with the VNS than they did in the active case with the Chariots.

5.3 Survey Results

To gather a more qualitative vision of the participant's time with the Chariot system and VNS, after they experienced each test condition they filled out a 16 question questionnaire comprising of items from the NASA-Task Load Index(TLX) and the System Usability Scale(SUS). The first 6 questions were from the NASA-TLX which score's systems and tasks based on a different types of demand(physical,mental,and temporal) and participant's emotional responses per question. Questions are scored on a likert scale of 1 to 7 with 1 meaning minimal effort and 7 being maximum effort being exerted on the participant's part. The total score for the system is calculated by averaging the responses for all the questions and should be interpreted as the lower the score the less strenuous the task is. The "task" in this study's case was prompted to the participant as being noticing and reacting to the notifications from each respective system and not their enjoyment of or performance in the VR game or video.

The SUS is a 10 statement survey that states generalized phrases(ie " I think that I would like to use this system frequently") to gather a more holistic view of the participant's experience with the system. The entries for this portion of the survey are scored on a scale of 1 to 10 with 1 being strongly disagree and 10 being strongly agreeing. The 10 statements of the survey alternate between both positive and negative responses to gauge both what the user's liked and disliked about the system in question (question 3 being "I thought the system was easy to use" vs question 6 being ". I thought there was too much inconsistency in this system"). The SUS is typically administered with a likert scale of 1 to 5 but we elected to have the likert scale be from 1 to 10 for a more fine-grain response set. To score the SUS survey, the 1 to 10 scores are remapped to values between 1 and 5 but allowing for non-integer answers. The even numbered questions are then summed and have their total be subtracted from 25, followed by the odd questions being summed and then subtracting 5 from their total. Those two values are then summed and multiplied by 2.5 to give a value from 0 to 100. The way to interpret this score is that a lower total means that the participant's found the system unusable and a higher score means they found the system very usable for the scenario they just experienced.

5.3.1 NASA-TLX Responses

Table 9.Descriptive Statistics for the collected NASA-TLX questions and their total scores.

Question/Score	Mean Value(out of 7)	Std deviation	N
Question 1	1.966	1.292	89
Question 2	1.820	1.820	89
Question 3	2.056	1.540	89

Question/Score	Mean Value(out of 7)	Std deviation	N
Question 4	1.989	1.496	89
Question 5	1.697	1.237	89
Question 6	5.243	1.565	89
Total	2.546	0.921	89

Following a similar procedure to the performance metrics for the users we first tested the responses for each individual question and their total scores for normality to determine the type of test to administer to find significance.

Table 10. Results of the Shapiro-Wilkes test for normality on the responses for the NASA-TLX and their scores.

Shapiro-Wilk Test for Normality			
Question/Score	statistic	Degrees of freedom	Significance (p)
Question 1	.879	89	<0.001
Question 2	.755	89	<0.001
Question 3	.690	89	<0.001
Question 4	.713	89	<0.001
Question 5	.698	89	<0.001
Question 6	.627	89	<0.001
Total score	.824	89	<0.001

Now knowing that all of our responses to the NASA-TLX are non-normal we applied Friedman's to each questions and the total score to see if there was any significant variances in the answers between the 4 conditions.

Table 11.Results of Friedman's on the responses for the NASA-TLX and their scores.

Question/score	N	Chi-square	df	Asymp. Significance
Question 1	19	23.884	3	<0.001
Question 2	19	18.405	3	<0.001
Question 3	19	24.613	3	<0.001
Question 4	19	17.18	3	<0.001
Question 5	19	13.219	3	0.004
Question 6	19	8.679	3	0.034
Total	19	22.030	3	<0.001

With significance being found within each question's responses, we conducted the Wilcoxin Signed-Rank Test the Bonferroni Adjustment to see where the significance between each group was. For clarity and discussion purposes the tables will be split by question.

Table 12.Average scores for Question 1 of the NASA-TLX for each test condition.

Condition	Response average (n=19)
Active case + Chariot	2.105
Active case + Visual	2.789
Passive case + Chariot	1.421
Passive case+ Visual	1.894

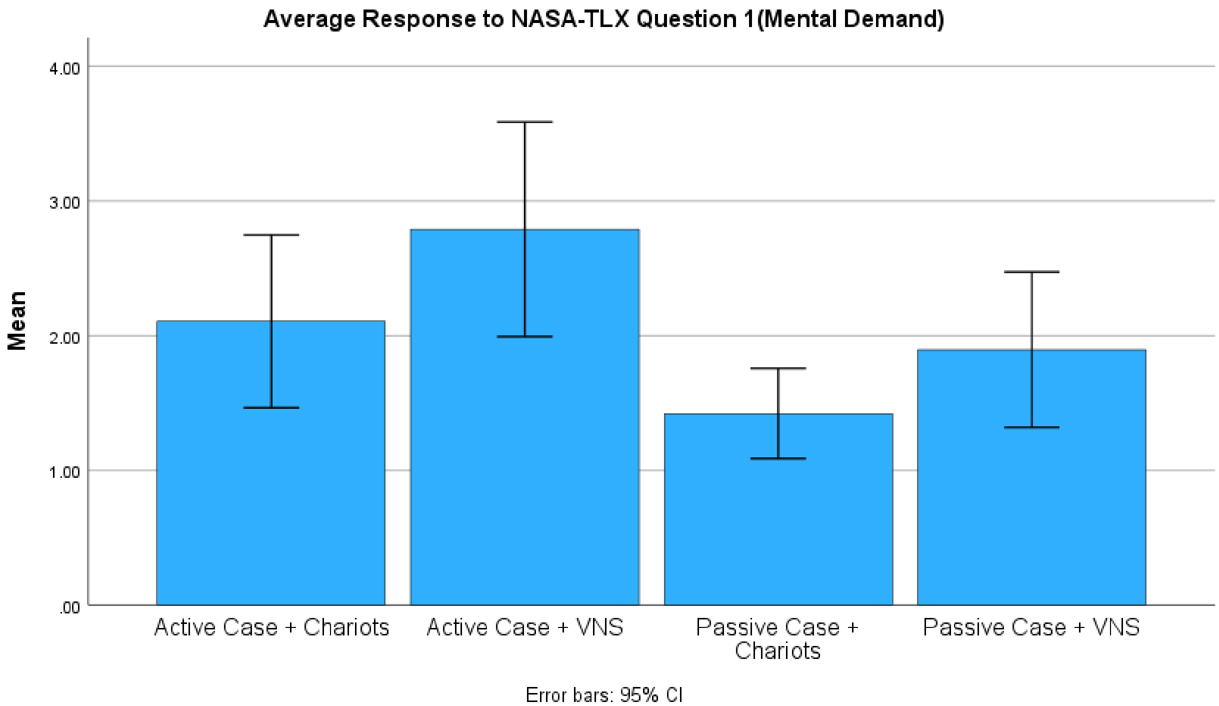

Figure 14. Average Response to NASA-TLX Question 1 (Mental Demand).

Table 13. Results of the Wilcoxon-Signed Rank Test for the NASA-TLX question 1.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-3.328	<0.001	0.00833	Significant
Passive Case + VNS	Active Case + VNS	-3.082	0.002	0.01	Significant
Passive Case + Chariots	Active Case + Chariots	-3.066	0.002	0.0125	Significant
Active Case + VNS	Active Case + Chariots	-2.336	0.019	0.0167	Not Significant
Passive Case + Chariots	Passive Case + VNS	-1.913	0.056	0.025	Not Significant
Passive Case + VNS	Active Case + Chariots	-1.29	0.197	0.005	Not Significant

Question 1 of the NASA-TLX is about the mental demand on the participant's part to notice the notifications that they experienced for that test condition. Significances were found between the VNS in the active case and the Chariots in the passive case, as well as when comparing both system's passive and active case responses. This was an expected outcome since the passive and active conditions were to put participants under different levels of interaction with the VE to see how it effected their bystander awareness.

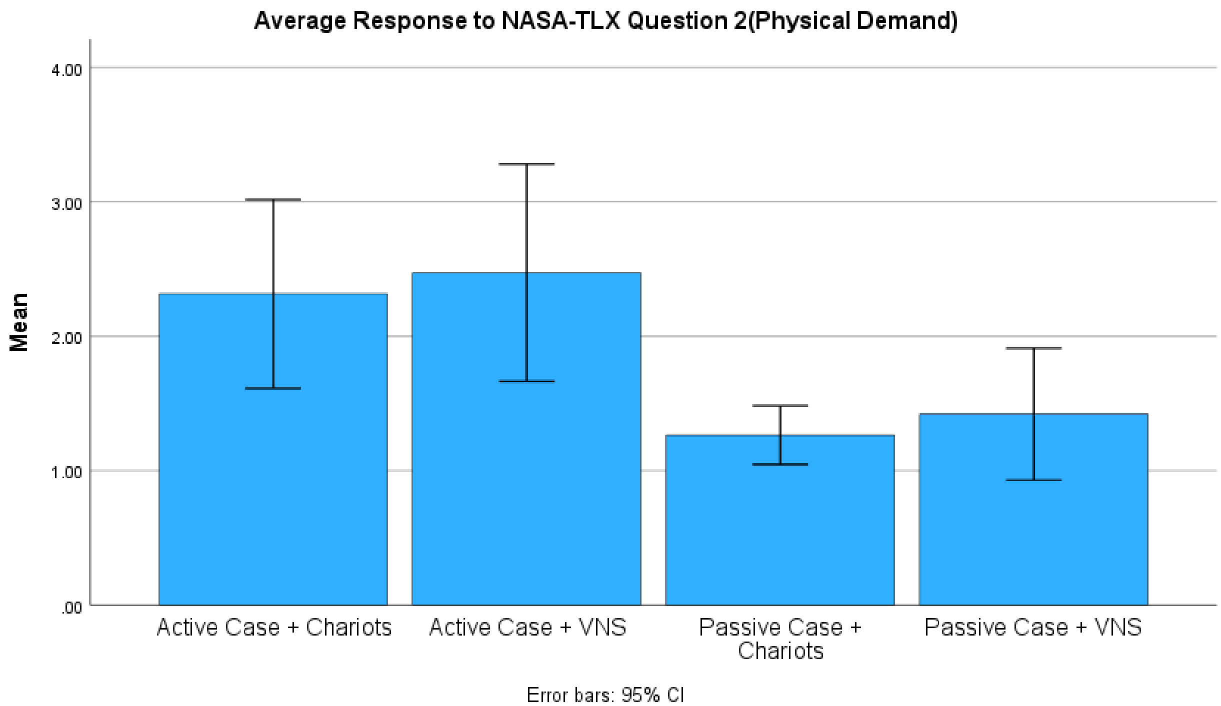

Figure 15.Average response to NASA-TLX question 2(Physical Demand).

Table 14.Average scores for Question 2 of the NASA-TLX for each test condition.

Condition	Response average (n=19)
Active case + Chariot	2.316
Active case + Visual	2.474
Passive case + Chariot	1.263
Passive case+ Visual	1.421

Table 15.Results of the Wilcoxon-Signed Rank Test for the NASA-TLX question 2.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + Chariots	-3.001	0.003	0.008333333	Significant
Passive Case + VNS	Active Case + VNS	-2.989	0.003	0.01	Significant

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-2.825	0.005	0.0125	Significant
Passive Case + VNS	Active Case + Chariots	-2.524	0.012	0.016666667	Significant
Active Case + VNS	Active Case + Chariots	-0.676	0.499	0.025	Not Significant
Passive Case + Chariots	Passive Case + VNS	-0.351	0.726	0.05	Not Significant

Question 2 of the NASA-TLX covers the physical demand on the participant to complete the task in question. Once again, similar to question 1 we find that demand is significantly higher for both systems when comparing them against themselves across the different conditions as well as when comparing across systems and conditions. Similar to what was stated in the findings of question 1, these significances were expected since the purpose of the passive and active cases were to subject participants to different levels of physical demand to see it's effect on their bystander awareness.

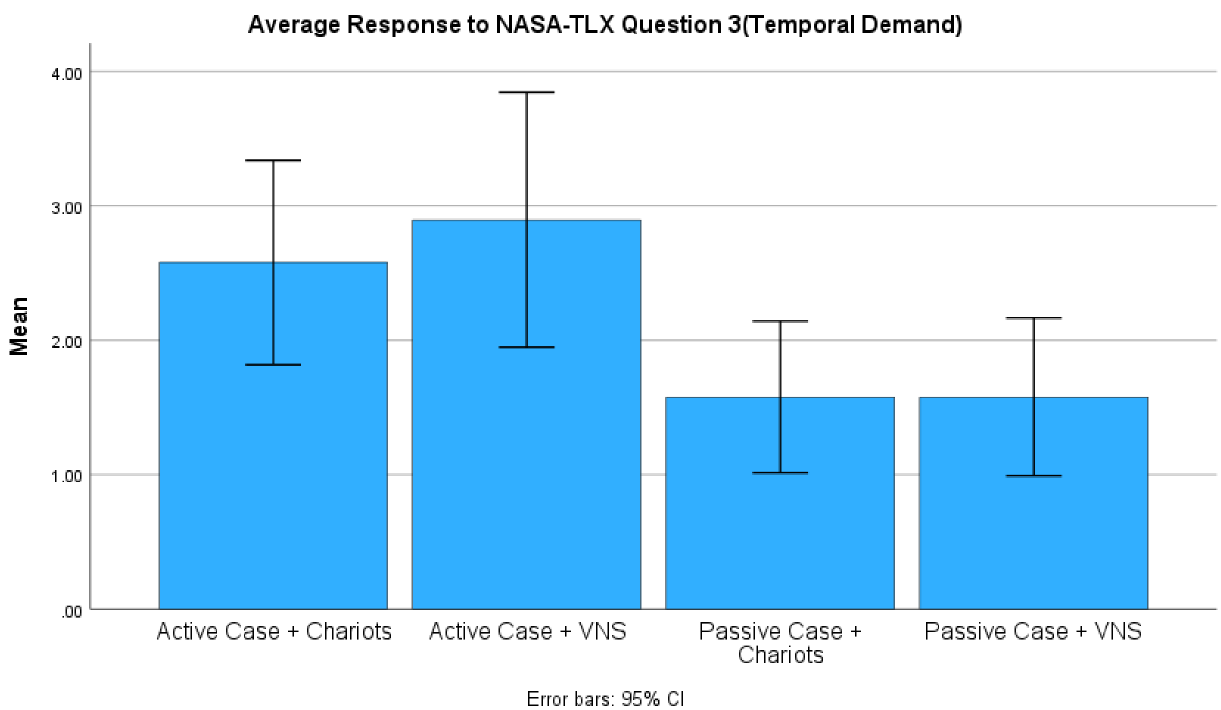

Figure 16. Average response to NASA-TLX question 2 (Physical Demand).

Table 16. Average scores for Question 3 of the NASA-TLX for each test condition.

Condition	Response average (n=19)
Active case + Chariot	2.579
Active case + Visual	2.895
Passive case + Chariot	1.579
Passive case+ Visual	1.579

Table 17. Results of the Wilcoxon-Signed Rank Test for the NASA-TLX question 3.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + Chariots	-3.111	0.002	0.008333333	Significant
Passive Case + VNS	Active Case + Chariots	-2.989	0.003	0.01	Significant
Passive Case + VNS	Active Case + VNS	-2.694	0.007	0.0125	Significant
Passive Case + Chariots	Active Case + VNS	-2.675	0.007	0.016666667	Significant
Active Case + VNS	Active Case + Chariots	-1.15	0.499	0.025	Not Significant
Passive Case + Chariots	Passive Case + VNS	-0.378	0.726	0.05	Not Significant

Question 3 of the NASA-TLX covers the temporal demand of the participant while completing their task. Temporal demand is the demand of the user to act quickly or hurried, which is how it is worded in the survey(How hurried or rushed was the pace of the task). Here we find significance once again when comparing each system against itself between conditions as well as when comparing across both systems and conditions. We can take these significances to mean that when playing the game with either system participants felt more rushed as when compared to when they were watching the video.

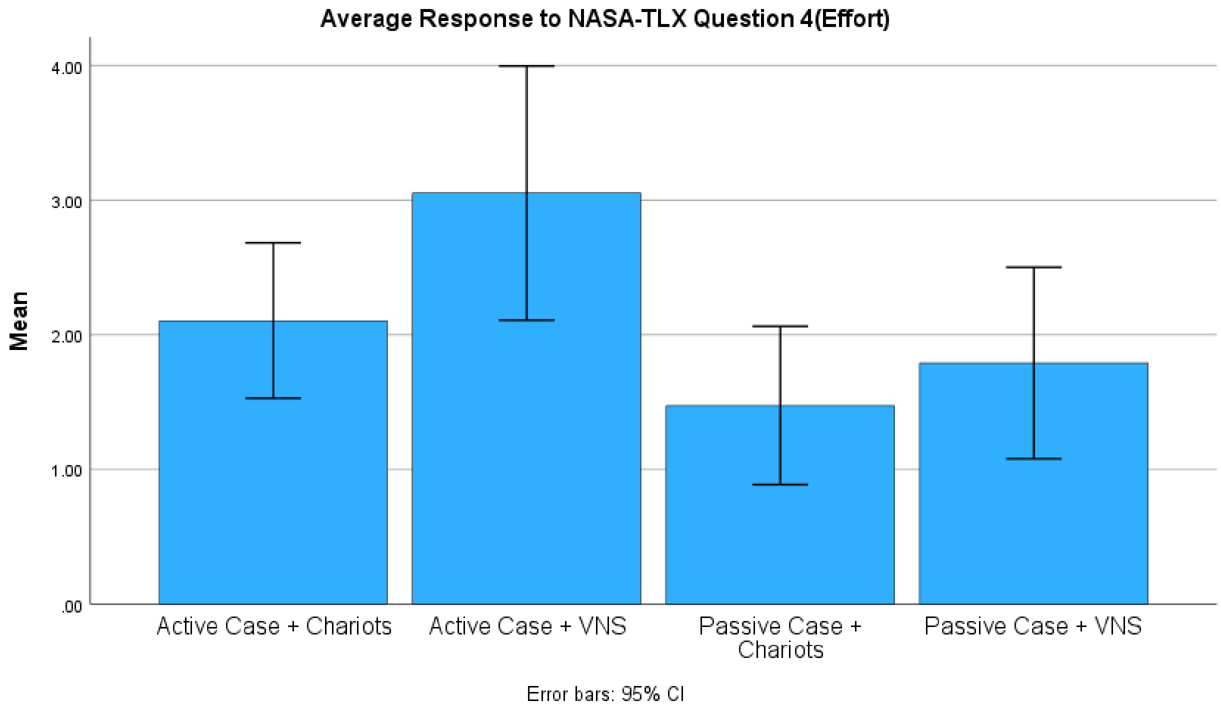

Figure 17.Average response to NASA-TLX question 4(Effort.).

Table 18.Average scores for Question 4 of the NASA-TLX for each test condition.

Condition	Response average (n=19)
Active case + Chariot	2.105
Active case + Visual	3.052
Passive case + Chariot	1.474
Passive case+ Visual	1.789

Table 19.Results of the Wilcoxon-Signed Rank Test for the NASA-TLX question 4.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-3.079	0.002	0.008333333	Significant

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + VNS	Active Case + VNS	-2.65	0.008	0.01	Significant
Active Case + VNS	Active Case + Chariots	-2.434	0.015	0.0125	Not Significant
Passive Case + Chariots	Active Case + Chariots	-2.113	0.035	0.016666667	Not Significant
Passive Case + Chariots	Passive Case + VNS	-1.387	0.165	0.025	Not Significant
Passive Case + VNS	Active Case + Chariots	-1.116	0.265	0.05	Not Significant

Question 4 of the NASA-TLX covers the effort needed by the participant to complete the task at hand. No significance is found when comparing the systems against each other across the active and passive conditions, for Chariots across both conditions, and for the passive visual and active haptics cases. The only significance found here was with the VNS when comparing results between the passive and active conditions. This means that users felt more annoyed with the appearance of the red bars during the game than they did when watching the video.

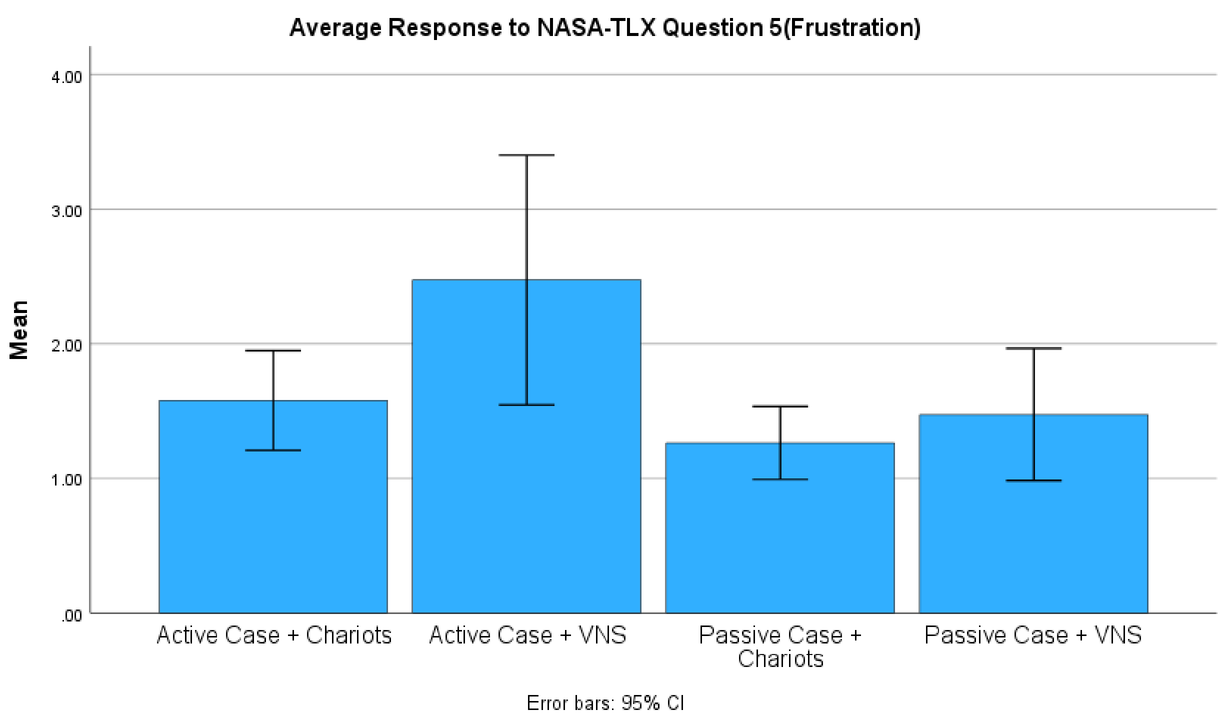

Figure 18. Average response to NASA-TLX question 5 (Frustration).

Table 20.Average scores for Question 5 of the NASA-TLX for each test condition.

Condition	Response average (n=19)
Active case + Chariot	1.578
Active case + Visual	2.473
Passive case + Chariot	1.263
Passive case+ Visual	1.473

Table 21.Results of the Wilcoxon-Signed Rank Test for the NASA-TLX question 5.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-2.671	0.008	0.008333333	Significant
Passive Case + VNS	Active Case + VNS	-2.565	0.01	0.01	Significant
Active Case + VNS	Active Case + Chariots	-1.992	0.046	0.0125	Not Significant
Passive Case + Chariots	Active Case + Chariots	-1.721	0.085	0.016666667	Not Significant
Passive Case + Chariots	Passive Case + VNS	-1.667	0.096	0.025	Not Significant
Passive Case + VNS	Active Case + Chariots	-0.796	0.426	0.05	Not Significant

Question 5 of the NASA-TLX covers the frustration level the participant experienced while using the system. The significance found in this test was between the passive case with the Chariots and the active case with the VNS, as well as between each case with the VNS. We can possibly explain these significances since it is a comparison between the least visually taxing condition with the video being a calm paced video and the most visually taxing condition, the rapid paced video game with flying fruit and the flashing red bars.

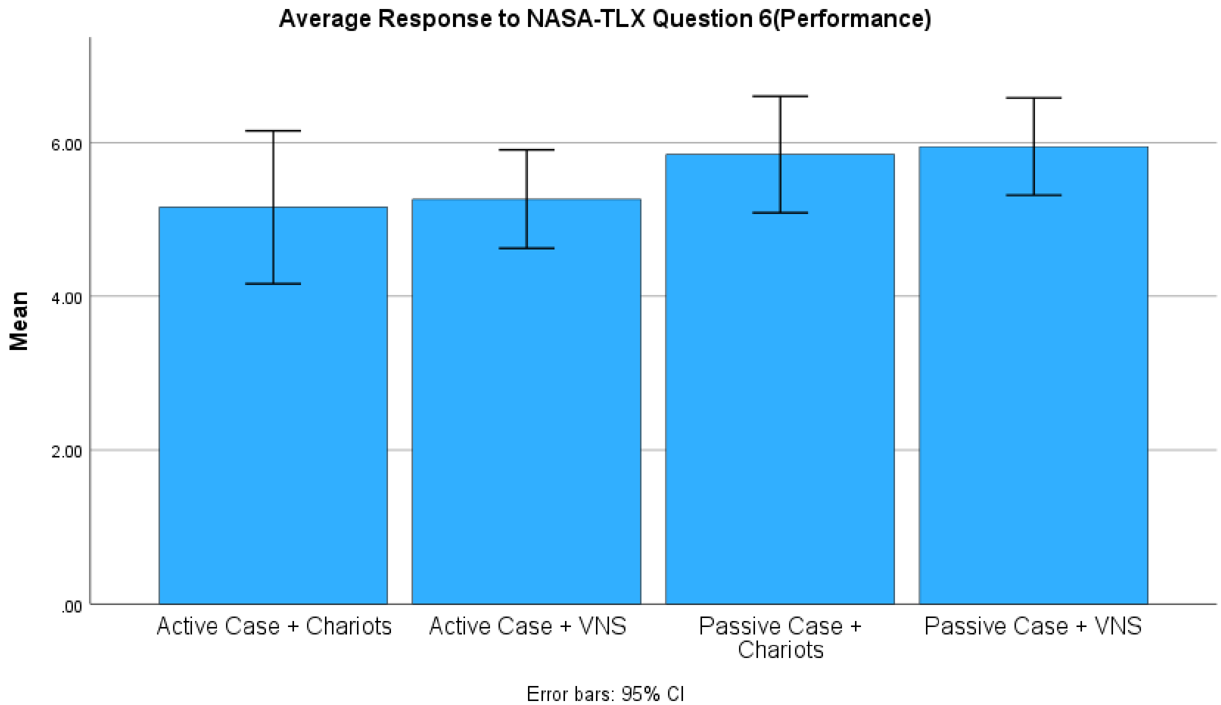

Figure 19. Average response to NASA-TLX question 6(Performance).

Table 22. Average scores for Question 6 of the NASA-TLX for each test condition.

Condition	Response average (n=19)
Active case + Chariot	5.1579
Active case + Visual	5.2632
Passive case + Chariot	5.8421
Passive case+ Visual	5.9474

Table 23.Results of the Wilcoxon-Signed Rank Test for the NASA-TLX question 6.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + VNS	Active Case + VNS	-2.228	0.026	0.008333333	Not Significant

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-2.088	0.037	0.01	Not Significant
Passive Case + VNS	Active Case + Chariots	-1.944	0.052	0.0125	Not Significant
Passive Case + Chariots	Active Case + Chariots	-1.273	0.203	0.016666667	Not Significant
Passive Case + Chariots	Passive Case + VNS	-0.275	0.784	0.025	Not Significant
Active Case + VNS	Active Case + Chariots	-0.2563	0.8	0.05	Not Significant

Question 6 of the NASA-TLX is about how successful the participant thought they did at performing the task in question. No statistical significance was found by Type-1 error. This can be interpreted to mean that participants on average did not feel drastically about their performance with each system regardless of the case they were in.

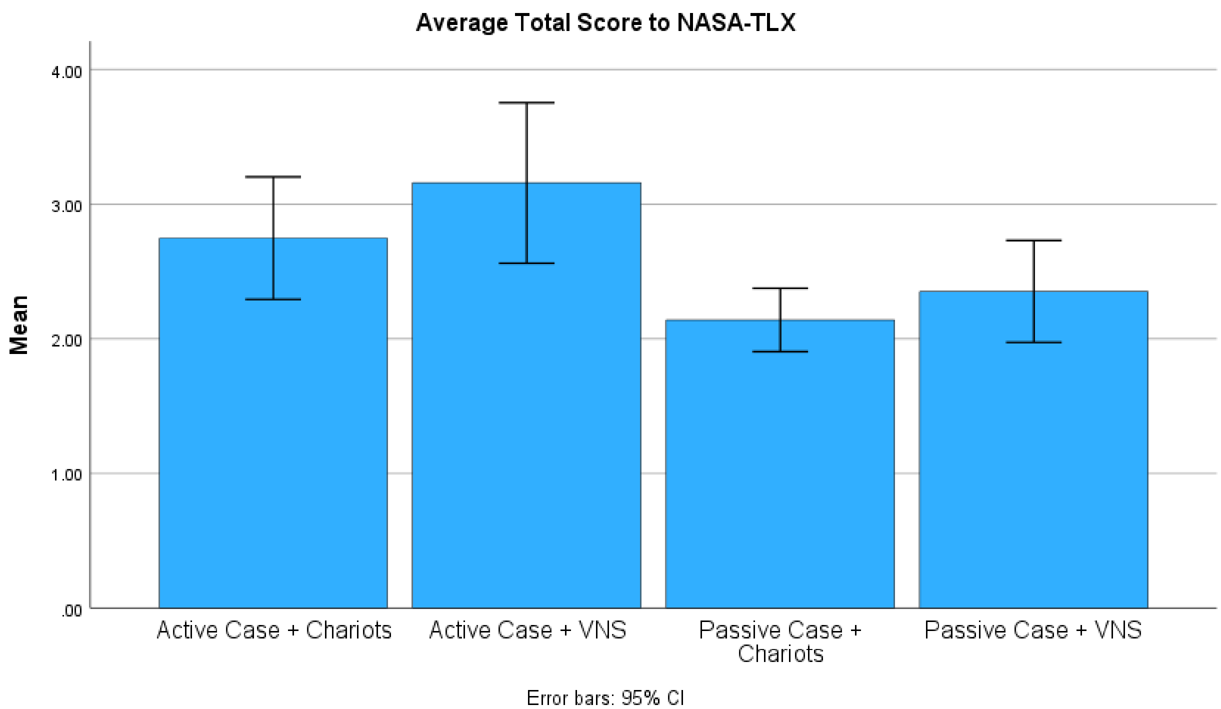

Figure 20.Average total score to NASA-TLX by condition.

Table 24.Average Total scores for the NASA-TLX for each test condition.

Condition	Total score average (n=19)
Active case + Chariot	2.7
Active case + Visual	2.992
Passive case + Chariot	2.116
Passive case+ Visual	2.367

Table 25.Results of the Wilcoxon-Signed Rank Test for the total scores of the NASA-TLX.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + VNS	Active Case + VNS	-3.466	0.001	0.008333333	Significant
Passive Case + Chariots	Active Case + VNS	-3.417	0.0001	0.01	Significant
Passive Case + Chariots	Active Case + Chariots	-3.02	0.003	0.0125	Significant
Passive Case + VNS	Active Case + Chariots	-2.214	0.027	0.016666667	Not Significant
Passive Case + Chariots	Passive Case + VNS	-1.827	0.068	0.025	Not Significant
Active Case + VNS	Active Case + Chariots	-0.296	0.768	0.05	Not Significant

Looking at the total scores of the NASA-TLX we find that as expected from the previous findings that there is no significance between the perceived difficulty of noticing the notifications on the participant’s part when comparing the Chariots to the VNS when comparing them in the same conditions. The significances here show that participants found the task loads of each system higher when in the passive case than in the active case for both systems as well as when comparing the task load of the passive case with the Chariots and the active case with the VNS. These significances can possibly be explained since the active case requires the participant to keep track of several elements of the VE(their sword swings, aiming of the gun, movement of the fruits, etc.) where as in the passive scene all the participant is expected to do is just sit back and watch the video.

5.3.2 SUS Responses

Table 26.Descriptive Statistics of the responses to the SUS survey.

Question/total score	Mean Value(out of 7)/ Mean Score (Out of 10)	Std deviation	N
Question 1	7.067	2.383	89
Question 2	1.842	1.499	89
Question 3	8.303	2.414	89
Question 4	1.561	1.167	89
Question 5	8.292	2.17	89
Question 6	2.101	1.610	89
Question 7	8.562	1.936	89
Question 8	2.618	2.338	89
Question 9	8.135	2.133	89
Question 10	1.8427	1.205	89
Total Score	83.770	13.888	89

Above are the averages and standard deviation for all SUS responses reported by the participants. Similar to the rest of the data prior to this we checked it for normality to see what type of statistical test to run.

Table 27.Results of the Shapiro-Wilkes test on the Responses to the SUS.

Question/total score	Statistic	N	Significance
Question 1	0.920	89	<0.001
Question 2	0.614	89	<0.001
Question 3	0.722	89	<0.001
Question 4	0.551	89	<0.001
Question 5	0.841	89	<0.001
Question 6	0.722	89	<0.001
Question 7	0.765	89	<0.001
Question 8	0.714	89	<0.001
Question 9	0.831	89	<0.001
Question 10	0.726	89	<0.001
Total Score	0.908	89	<0.001

With the lack of normality in the distribution in the data established, we then ran Friendman's ANOVA on the data to see where there are any significant differences in the answers participants provided for each test condition.

Table 28.Results of the Friedman's ANOVA test on the Responses to the SUS.

Question/score	N	Chi-Square	df	Asymp. Significance
Question 1	19	8.719	3	0.033
Question 2	19	19.982	3	0.003
Question 3	19	9.378	3	0.025

Question/score	N	Chi-Square	df	Asymp. Significance
Question 4	19	0.054	3	0.997
Question 5	19	8.433	3	0.038
Question 6	19	8.550	3	0.036
Question 7	19	0.888	3	0.828
Question 8	19	9.976	3	0.019
Question 9	19	12.488	3	0.006
Question 10	19	5.645	3	0.130
Total Score	19	12.537	3	0.006

As opposed to the NASA-TLX findings where all the questions came back with significant variances, some questions of the SUS came back without any statistically significant variances.

Table 29. Results of the Wilcoxon-Signed Rank Test for the first statement of the SUS.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-2.338	0.019	0.008333333	Not Significant
Active Case + VNS	Active Case + Chariots	-1.926	0.054	0.01	Not Significant
Passive Case + Chariots	Passive Case + VNS	-1.627	0.104	0.0125	Not Significant
Passive Case + Chariots	Active Case + Chariots	-1.125	0.261	0.016666667	Not Significant
Passive Case + VNS	Active Case + Chariots	-1.039	0.299	0.025	Not Significant
Passive Case + VNS	Active Case + VNS	-1.035	0.301	0.05	Not Significant

Table 30.Results of the Wilcoxon-Signed Rank Test for the third statement of the SUS.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-2.19	0.028	0.008333333	Not Significant
Passive Case + VNS	Active Case + VNS	-2.053	0.04	0.01	Not Significant
Passive Case + Chariots	Active Case + Chariots	-2.014	0.044	0.0125	Not Significant
Passive Case + VNS	Active Case + Chariots	-1.438	0.15	0.016666667	Not Significant
Passive Case + Chariots	Passive Case + VNS	-1.274	0.203	0.025	Not Significant
Active Case + VNS	Active Case + Chariots	-0.625	0.532	0.05	Not Significant

Table 31.Results of the Wilcoxon-Signed Rank Test for the sixth statement of the SUS.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-2.395	0.017	0.008333333	Not Significant
Passive Case + VNS	Active Case + VNS	-2.142	0.032	0.01	Not Significant
Active Case + VNS	Active Case + Chariots	-1.606	0.108	0.0125	Not Significant
Passive Case + Chariots	Passive Case + VNS	-1.078	0.281	0.016666667	Not Significant
Passive Case + Chariots	Active Case + Chariots	-0.66	0.509	0.025	Not Significant
Passive Case + VNS	Active Case + Chariots	-0.259	0.796	0.05	Not Significant

Table 32.Results of the Wilcoxon-Signed Rank Test for the eighth statement of the SUS.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-2.133	0.033	0.008333333	Not Significant
Active Case + VNS	Active Case + Chariots	-1.911	0.056	0.01	Not Significant
Passive Case + VNS	Active Case + VNS	-1.767	0.077	0.0125	Not Significant
Passive Case + Chariots	Passive Case + VNS	-1.741	0.082	0.016666667	Not Significant
Passive Case + VNS	Active Case + Chariots	-1.175	0.24	0.025	Not Significant
Passive Case + Chariots	Active Case + Chariots	-0.165	0.869	0.05	Not Significant

Table 33.Results of the Wilcoxon-Signed Rank Test for the ninth statement of the SUS.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-2.54	0.011	0.008333333	Not Significant
Passive Case + Chariots	Active Case + Chariots	-2.339	0.019	0.01	Not Significant
Passive Case + VNS	Active Case + VNS	-1.194	0.233	0.0125	Not Significant
Active Case + VNS	Active Case + Chariots	-1.109	0.268	0.016666667	Not Significant
Passive Case + Chariots	Passive Case + VNS	-0.986	0.324	0.025	Not Significant
Passive Case + VNS	Active Case + Chariots	-0.388	0.698	0.05	Not Significant

While initially showing significance with Friedman, the first,third,sixth, eighth, and ninth statements of the SUS came back to be not significantly different once we performed the Wilcoxon-Signed Rank Test with Holm's sequential bonferroni adjustment by Type-1 Error.

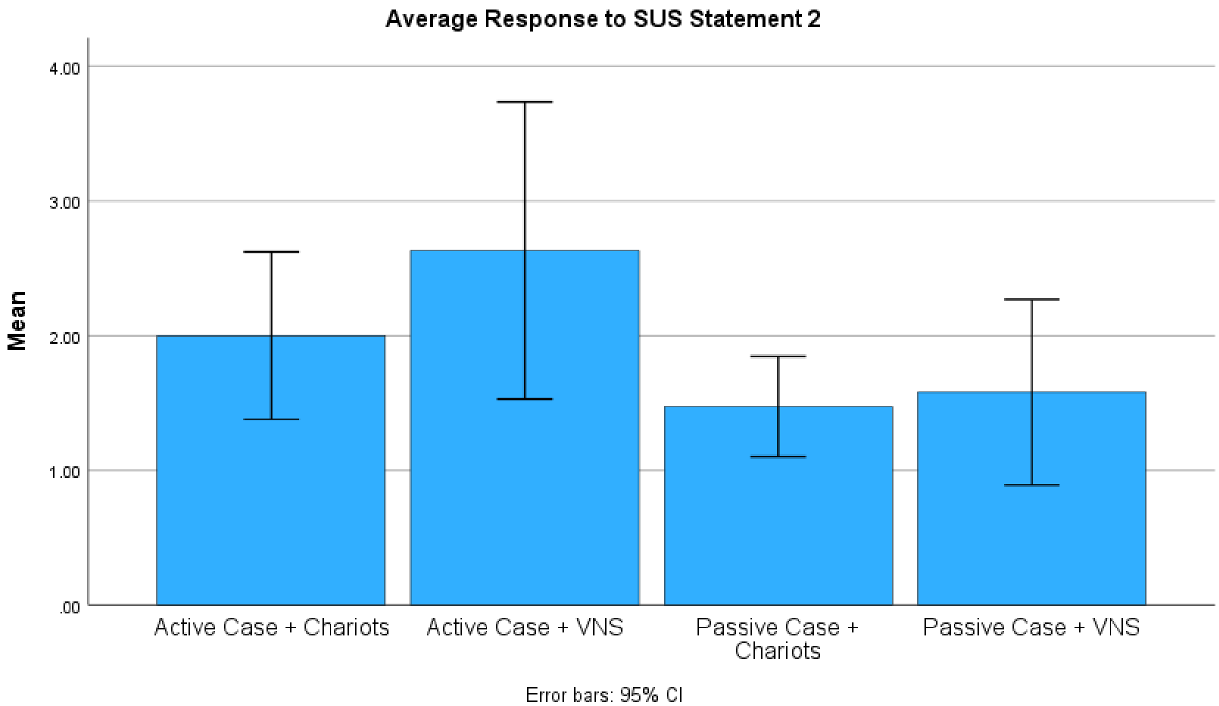

Figure 21. Average responses to SUS Statement 2 by condition.

Table 34. Average responses for the second statement of the SUS.

Condition	Total score average (n=19)
Active case + Chariot	2
Active case + Visual	2.6316
Passive case + Chariot	1.474
Passive case+ Visual	1.579

Table 35.Results of the Wilcoxon-Signed Rank Test for the second statement of the SUS.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + VNS	Active Case + VNS	-2.699	0.007	0.008333333	Significant
Passive Case + Chariots	Active Case + VNS	-2.352	0.019	0.01	Not Significant
Passive Case + VNS	Active Case + Chariots	-2.017	0.044	0.0125	Not Significant
Passive Case + Chariots	Active Case + Chariots	-1.83	0.067	0.016666667	Not Significant
Active Case + VNS	Active Case + Chariots	-1.175	0.24	0.025	Not Significant
Passive Case + Chariots	Passive Case + VNS	-0.175	0.861	0.05	Not Significant

Statement 2 of the SUS asserts "I found the system unnecessarily complex." and significance was found by the Wilcoxon-Signed Rank Test with adjustments between the responses for the VNS with both the active and passive cases. We can interpret this significance to mean that participants found the VNS less user friendly when in the active case than in the passive case.

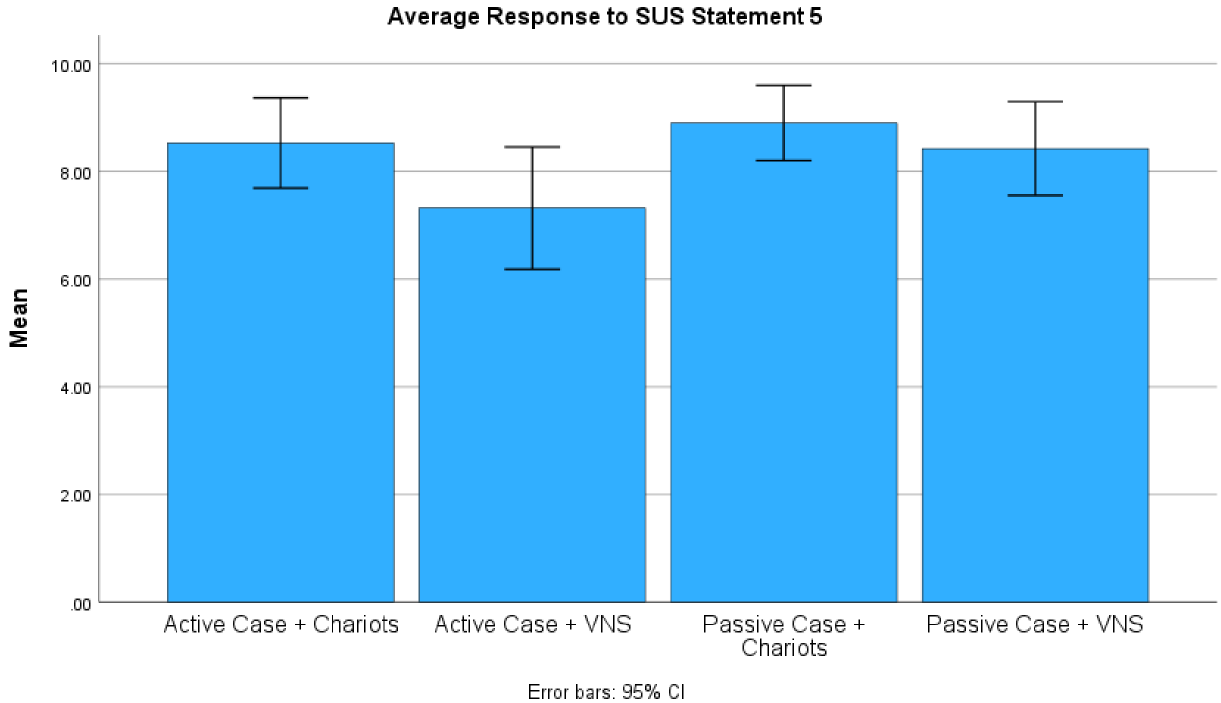

Figure 22. Average response to SUS statement 5 by condition.

Table 36. Average responses for the statement five of the SUS.

Condition	Response average (n=19)
Active case + Chariot	8.526
Active case + Visual	7.316
Passive case + Chariot	8.895
Passive case+ Visual	8.421

Table 37. Results of the Wilcoxon-Signed Rank Test for the total scores of the SUS.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-2.72	0.007	0.008333333	Significant

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + VNS	Active Case + VNS	-2.625	0.009	0.01	Significant
Active Case + VNS	Active Case + Chariots	-1.954	0.051	0.0125	Not Significant
Passive Case + Chariots	Active Case + Chariots	-0.815	0.415	0.016666667	Not Significant
Passive Case + Chariots	Passive Case + VNS	-0.549	0.583	0.025	Not Significant
Passive Case + VNS	Active Case + Chariots	-0.127	0.899	0.05	Not Significant

The results of the Wilcoxon-Signed Rank test for the fifth statement of the SUS found significance between the Passive haptic case and the Active visual case as well as between both cases using the VNS. Statement 5 is ""I found the various functions in this system were well integrated" and we can take the significances found here to be attributed to the same reason as in statement 2. The lower average response to this statement from participants indicates that they felt that the VNS was not as user friendly in the active case when compared to the passive case.

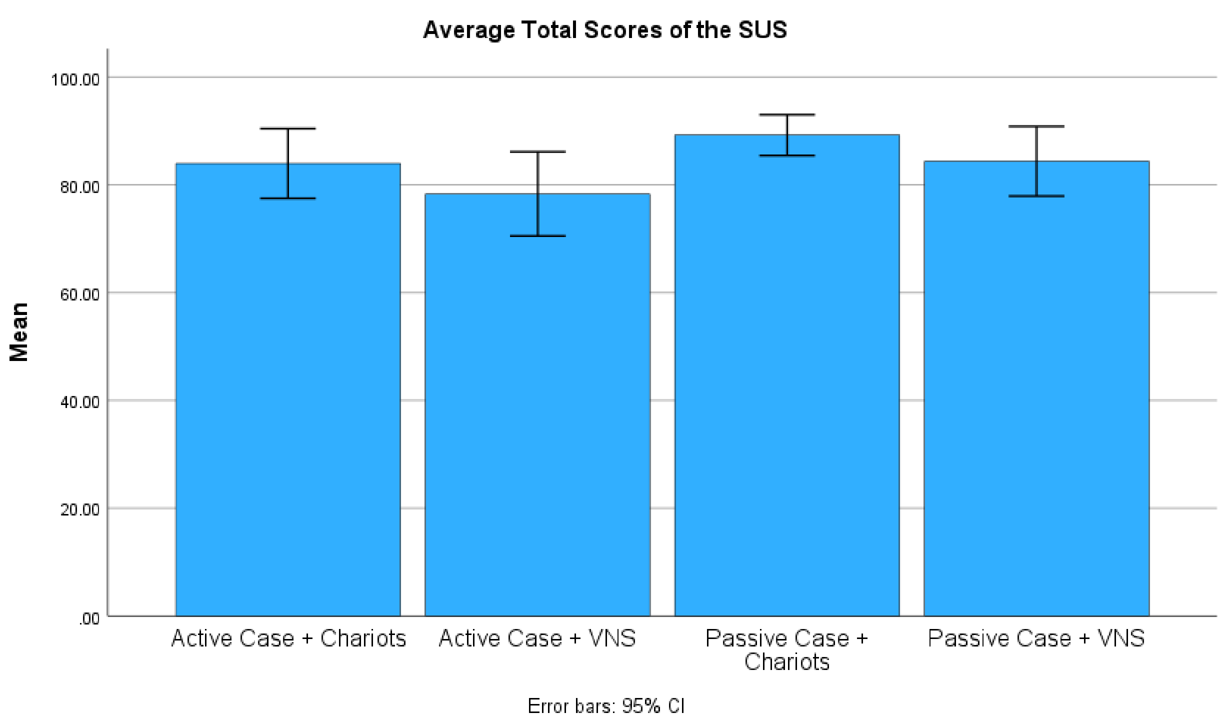

Figure 23. Average total scores of the SUS by condition.

Table 38.Average Total scores for the SUS..

Condition	Total score average (n=19)
Active case + Chariot	83.977
Active case + Visual	78.304
Passive case + Chariot	89.239
Passive case+ Visual	84.386

Table 39.Results of the Wilcoxon-Signed Rank Test for the total scores of the SUS.

Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + VNS	-3.072	0.002	0.008333333	Significant
Passive Case + VNS	Active Case + VNS	-2.615	0.009	0.01	Significant
Condition 1	Condition 2	Z	p	Required P for significance	Significant/ Not Significant
Passive Case + Chariots	Active Case + Chariots	-2.316	0.021	0.0125	Not Significant
Active Case + VNS	Active Case + Chariots	-1.546	0.122	0.016666667	Not Significant
Passive Case + Chariots	Passive Case + VNS	-1.207	0.227	0.025	Not Significant
Passive Case + VNS	Active Case + Chariots	-0.233	0.816	0.05	Not Significant

The results of the Wilcoxon-Signed Rank test for the total score of the SUS found significance between the Passive haptic case and the Active visual case as well as between both cases using the VNS. These findings tell us that when the VNS and the Chariots are in the same case , participants found that each system was comparable to each other in their usability. The presence of significances between the VNS in the Active case and both conditions in the passive case could tell us that they found the VNS less usable in the active case as compared to the passive.

CHAPTER SIX:DISCUSSION

6.1 Performance Metrics

6.1.1 Missed notifications

The results of the statistical tests we did with the number of missed notifications for each test condition being not significant can be interpreted to mean that a participant using the Chariots will notice passerby coming close to them with roughly the same level of accuracy as they would using the VNS. With the VNS being analogous to already established and implemented VR safety features this can be taken to mean that the Chariots performed on par with these systems when it comes to identifying passerby.

6.1.2 Reaction Time

With the results from the statistical analysis finding that the response time for the Chariots system being slower than the VNS when in the active condition we can interpret this to mean that the Chariots may be better suited for more passive VR activities. Looking at the other pairings with significance of test conditions we do find further support for this theory. We do find significance in the difference between the Passive and Active haptic cases, with the Passive haptic case having the faster of the two reaction times and the fastest of all the test conditions. This paired with one's participant comment "I was unsure if I had seen a visual notification during the video but when I did see it, it was very shocking and startled me". This comment and the findings from the statistical tests can lead us to believe that the chariots would possibly be best paired with slower paced, physically passive VR activities such as taking a VR call or going through a VR experience like a virtual tour of a point of interest or watching a VR video.

6.2 NASA-TLX responses

6.2.1 Question 1

The results of the statistical testing did not find any significance between the VNS and Chariots when comparing the participants responses in the same conditions, so we can assume that in each condition both systems required similar amounts of mental resources. The other pairings of conditions do however paint an interesting picture for understanding the mental load on the participants when in VR. For both systems, the mental workload is significantly higher when comparing their passive conditions to their active ones. What this means is that in general, participants will have to devote more mental resources to being aware of their environment while actively participating with a VE than if they were passively participating with it. Combining the results of the pairing of the Passive Visual Case and the Active Haptic case and our findings from table 4 we can say that for a comparable mental workload a participant actively participating with a VE using the Chariot system is just as aware of their surroundings as a participant passively interacting with the VE and using the VNS. This finding could have applications in areas such as VR collaboration or working while in VR as this means that users of the Chariots system will be able to work and focus on tasks while still being as aware of their surroundings if they were just sitting mostly still and looking around with the VNS.

6.2.2 Question 2

No statistical significance was found when comparing the VNS and Chariots across the same conditions meaning that the physical demand of the systems was indifferent for both conditions. Significance was found when comparing the systems against themselves across the active and passive conditions. These findings are in line with expectations as participants during the active case are expected to swing a sword and shoot a gun at targets as well as hit the button to mark down that they received a notification, whereas in the passive case the only interaction they are expected to do is look around casually and press the button to mark that they noticed a passerby.

6.2.3 Question 3

Continuing the trend from the earlier questions, no significance is found between the Chariots and VNS when compared in the same scenarios. Similarly, another trend that we see continues from the previous question is that temporal demand is higher across both systems when comparing their active results to their own respective passive results. This follows common sense since during the active case the participant's attention would be called back to the game due to its fast nature so it would follow that the participant would feel rushed to mark their notification in order to attend to the matters of the game. This finding can be seen as a positive for both systems since in the active case the user is gesticulating their arms and turning about in the VE rapidly, actions that if a passerby or object is in the way of could lead to injury or damage to property.

6.2.4 Question 4

As mentioned earlier question 4 of the NASA-TLX asks the user how much effort they put into the task. "Effort" in the questionnaire is not defined but we can take it to mean some combination of the mental,physical,and temporal demands reported from the previous three questions. The way a participant weighs each of these demands together when forming this score is done passively and unconsciously so this score can be seen as how hard they think they worked subjectively when using either of the systems in each of the conditions. With this in mind, we can see that participants did not report significantly different amounts of effort between the VNS and Chariots when using the systems in the same cases. With no statistical significance between the active and passive haptic cases this means that regardless of if the player was moving around rapidly and shooting the targets or just sitting and watching the video they were exhibiting comparable amounts of effort to stay aware of their surroundings. This stands in stark contrast to the VNS where users did have to use significantly more effort when in the active case than in the passive. This finding lines up with participant comments given after they completed all test conditions, several of them citing that having to keep checking the sides of their vision every few seconds to make sure they didn't miss any notifications while playing the game or for one participant who said they were unsure if they were confusing the visual stimuli with the fast moving targets of the game.

6.2.5 Question 5

With no statistical significance found again between the VNS and Chariots when in the same condition we can say that they gave indistinguishable levels of frustration to users regardless of activity. The significance of this test was found between the Active visual case and both passive cases. This is inline with some comments made during the game where a participant was noted to show annoyance with the red bars appearing during the game as the occluded part of the game. The lack of significance between the passive and active haptic conditions can be interpreted as users feeling the same about the Chariots across in both conditions which could possibly point towards the Chariots being a more generally acceptable system for more scenarios from a user experience perspective. Like with the findings of question 4, statistical significance was found between both conditions of the VNS with the active case reporting the highest.

6.2.6 Question 6

Since participants were not aware of the number of notifications they had missed or seen we can interpret this score as how confident the participants were in their performance using each system. While initially showing significance in the Friendman's ANOVA test, applying the Holm's Sequential Bonferroni Adjustment we find that there is no significant difference between the participant's reported confidence across any of the test conditions due to Type-1 error. This means that user's felt similarly confident using the VNS system which can be seen as analogous to already implemented systems as they were using the Chariots. The lack of significance between each system and itself in different conditions could be seen as a positive for both systems as this could point to both systems being usable in either a passive or active scenario.

6.2.7 Total scores

With no statistical significance found between the VNS and Chariots in the same condition for the total score we can take this to mean that by the standards of the NASA-TLX the two systems are analogous in how effective they are in keeping the participant aware of their surroundings. Statistical significance found between the Chariots' performance in the active and passive cases can also lend credence to the notion that they may be better suited for more passive VR activities. We also see a repeat of the significance found in question 1 where the Active haptic case is not statistically different from the Passive visual case, which can again be taken to mean that a person performing a physically intense task in VR using the chariots is working just as hard as a person who is just sitting still while in VR to stay aware of their environment.

6.3 System Usability Scale responses

6.3.1 Non-Significant Responses

Interestingly, when compared to the NASA-TLX responses, several of the statements of the SUS came back as not significantly different when put through Friedman Statement 4 of the SUS says "I think that I would need the support of a technical person to use this system". We can interpret this to mean that the ease of setting up for both systems are not significantly different for participants. While for the VNS this was expected since it did not require any action on the participant's part to set up or use, this is a positive sign for the Chariot system since it required the participant to put on and move about while using new piece of technology relative to them. Statement 7 is "I would imagine that most people would learn to use this system easily" and the lack of significance plus the higher average score of the question means that participants think that learning the Chariots systems functionality is as comparably easy as learning the VNS's. Statement 10 is "I needed to learn a lot of things before I could get going with this system" which follows with the responses given to statement 7. What we can draw from the lack of significance within these responses is that the Chariots user experience and approachability is not significantly harder or easier as the VNS which is analogous to already on the market and established VR safety features.

While initially showing significance through Friedman, the first, third,sixth, eighth,and ninth statements of the SUS came back as being not significantly different when put through the Wilcoxon-Signed Rank Test with Holm's sequential bonferroni adjustment by Type-1 Error. The first statement is "I think that I would like to use this system frequently" which had a higher average response score which means that on average users would like to adopt and use both the VNS and Chariots systems. Statement three is "I thought the system was easy to use" which the lack of significance can point to mean that users found both systems comparable in use which follows with the results of statement one. Statement six is "I thought there was too much inconsistency in this system" and we can take the lack of significance along with the low average score of the question to mean that users felt that both systems were consistent in their functionality from their perspective. Statement eight is "I found the system very cumbersome to use" which for the VNS alone is unimportant since the system is wholly virtual and does not require and physical manipulation by the participant but since the Chariot system has a physical component to it ,this can mean that the ergonomics of the system are suited well enough to be analogous to a wholly virtual one. Statement nine is "I felt very confident using the system" which is similar to question 4 of the NASA-TLX. While comments were made by select participants about confusion while using the VNS, the higher average response to the statement and across all conditions showed that participants were equally and very confident while using both systems.

6.3.2 Statement 2

Statement 2 of the SUS is ""I found the system unnecessarily complex." and the only significant difference in responses was between both conditions of the VNS. While the score for the VNS in the active case is the highest of the four conditions, it still is only at a value of 2.6 out of 10. We can take this to mean that at worst, participants on average found both systems presented as mildly complex to understand. The lack of significance between the Chariots in both cases also points it to it being possibly a generalizable solution for participants trying to stay aware of their surroundings while in VR from an approachability standpoint.

6.3.3 Statement 5

Statement 5 of the SUS is "I found the various functions in this system were well integrated". The significance of this test was found again between both cases of the VNS and the passive haptic case with the Active visual case. The significance found between the Passive haptic case and the active visual case shows that participants felt that the haptics of the passive case felt better integrated than the visuals into the active case. This finding can be interpreted in two way, either as a positive or as a negative of the visual case. Previous works in the area of bystander awareness have tried varying approaches of visual notifications to draw the attention of participants, with some theming the visuals to be part of the VE and others not making them cohesive with the VE. While blending the notification will aesthetically make them seem more integrated into the environment, this can lead to the situation where the participant will think the bystander is part of the VE. This can also be seen in several comments left by participants where they told the researcher that while they could see the visual notifications, they felt it would break their immersion in whatever activity they were doing. There is also merit in the idea of wanting the notifications to stand out from the VE to make sure that the participant recognizes it as something urgent. The lack of significance between the chariots in either case could also lend credence to the idea of somehow balancing a notification's importance while also not obstructing the virtual experience.

6.3.4 Total score

Significance was found in the total scores of the system in the same combinations as in statement 5. What we can draw from this is further support for the trend's we've seen in all the previous statements, both the VNS and chariots are comparable to each other when compared in the same conditions but it is across conditions where we can see their differences. The VNS scored significantly higher in the passive case than it did on the active case which can be interpreted to mean that participants preferred to use the VNS for the passive case rather than the active case, but participants also did not say the same for the Chariots. This could lead to the conclusion that while participants preferred to use the visual in the active case rather than the passive, they would rather use the Chariots in either condition.

6.4 Final Result Remarks

When looking at the performance metrics we find that participants recognized a comparable amount of passersby using the Chariots when compared to the VNS in both conditions. This tells us that when ignoring reaction time haptic feedback performed on par with visual feedback at maintaining a participants bystander awareness. Including reaction time into this comparison we find that participants noticed passersby faster with the VNS than with the Chariots, but only in the active case. Incorporating this with the findings of how many passersby were noticed we can say that while haptic feedback can keep participants aware of passersby to a similar level of visual feedback, visual feedback spurs a more immediate response from participants.

Looking at the survey responses we can see that for all entries the VNS and Chariots were not found to be significantly different when comparing them in the same case. The presence of significances when comparing the different test conditions however can give us a more in depth understanding of the relationship between the type of feedback and participant's ability to maintain bystander awareness. Demands on participants were universally higher when comparing the active case to the passive case within each system but the mental demand of the Chariots in the active condition were comparable to the mental demands of the VNS in the passive condition. This tells us that for a similar mental load a user could perform complex tasks in VR and stay aware of their surroundings with the Chariots as they would for being sedentary with the VNS. We also find that the Chariots drew comparable amounts of effort and frustration regardless of the test case they were in where the same cannot be said for the VNS. This can point us to believe that haptic feedback could be a suitable replacement for visual feedback for a general use bystander awareness system if at the cost of a slower reaction time to passersby.

CHAPTER SEVEN:FUTURE WORK

This work could be expanded upon in the future to create a more mobile and thus more generally applicable bystander awareness system for use with VR or with other situations where a participant's visual field is nearly all encompassed. The entirety of this study was done with the participant sitting down and staying in the same position for it's duration. While a realistic scenario for typical VR usage, advancements in VR inside-out tracking and mapping have popularized more mobile VR experiences. The implementation of a more compact and lightweight power source for each wristband would allow for the participant to walk around a physical space with them. That in combination with real-time proximity sensors such as IR or millimeter wave sensors could allow a user to physically walk around a VE with confidence that they won't bump into any other person or object in their environment.

This study could also be redone in the future with more of a continuum between the active and passive conditions. This study used a calm, slow paced VR video for its passive condition and a fast paced first person shooter for its active case. A future rendition of this study could use a slower paced more mentally challenging VR task or activity such as a puzzle game or faster paced more attention grabbing video to see how that changes the participant's reaction times and accuracy when using either visual or haptic notifications. As stated previously, this study was conducted sitting down and being stationary for it's duration. If done in a controlled environment and with the aforementioned additions to the system, participants could walk around in an empty room while in a VE and be presented with simulated notifications like this one to see which ones they noticed more often and how quickly it takes them to respond to it.

CHAPTER EIGHT:CONCLUSION

The Chariot system was designed to be a haptic feedback bystander awareness system to alert participants to oncoming passerby or obstructions in their immediate area that they can't see while in VR. Evaluating the system's performance with an n=24 user study against a visual analog found that while in terms of response time the visual notifications prompted a quicker response in both the active and passive conditions, the accuracy in which participants recognized the notifications of the two were found to not be significantly different. Survey results taken after each test condition found that when comparing the Chariots results to the VNS results there were no significant differences when they are both in the same condition. Statistical significance was found in the SUS response several times when comparing the VNS against itself in different conditions but this significance was not found in the responses for the Chariots. This leads to the finding that from a performance standpoint the VNS performed slightly better than the Chariots in one scenario but from a user experience standpoint participants preferred the Chariots better than the VNS. What we can take away from this is that haptic feedback can be used as a suitable replacement for visual feedback for maintain bystander awareness if only at the drawback of a slower reaction speed when user's are expected to perform rapid movements.

APPENDIX A: SURVEYS

A.1 Demographics Survey

Demographics Survey

1. What is your age?

2. What gender do you identify with?

3. Have you ever experienced cyber sickness when using a VR headset?

4. Are you in good physical health and have no physical disabilities or injuries, preventing you from completing the tasks that include playing a VR game with possibly both arms

A.2 Post VR Survey

Post-VR survey

Please answer the following questions in regards to the system used to make you aware of bystanders and the task it is referring is your awareness of said bystanders

1. Please ask the researcher for your user number

2. Which condition did you just experience

- ◯ Haptic/Passive
- ◯ Haptic/Active
- ◯ Visual/Passive
- ◯ Visual/Active

3. Please answer the following statements with 1 being minimal and 7 being maximum

	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7
How mentally demanding was the task?	◯	◯	◯	◯	◯	◯	◯
How physically demanding was the task?	◯	◯	◯	◯	◯	◯	◯
How hurried or rushed was the pace of the task	◯	◯	◯	◯	◯	◯	◯
How hard did you have to work to accomplish your level of performance?	◯	◯	◯	◯	◯	◯	◯
How insecure, discouraged, irritated, stressed, and annoyed were you?	◯	◯	◯	◯	◯	◯	◯
How successful were you in accomplishing what you were asked to do?	◯	◯	◯	◯	◯	◯	◯

For the following section please answer the statements with 1 being strongly disagree and 10 being strongly agree

4. I think that I would like to use this system frequently.

5. I found the system unnecessarily complex.

6. I thought the system was easy to use.

7. I think that I would need the support of a technical person to be able to use this system

8. I found the various functions in this system were well integrated.

9. I thought there was too much inconsistency in this system.

10. I would imagine that most people would learn to use this system very quickly.

11. I found the system very cumbersome to use.

12. I felt very confident using the system.

13. I needed to learn a lot of things before I could get going with this system.

APPENDIX B: UCF IRB DOCUMENTATION

UNIVERSITY OF CENTRAL FLORIDA

Institutional Review Board
FWA00000351
IRB00001138, IRB00012110
Office of Research
12201 Research Parkway
Orlando, FL 32826-3246

<u>APPROVAL</u>

September 3, 2024

Dear Jose-Valentin Sera-Josef:

On 9/3/2024, the IRB reviewed the following submission:

Type of Review:	Initial Study, Categories 4, 6, 7a, 7b
Title:	Data collection for Increasing Bystander and Environmental Awareness through the use of Haptic Feedback
Investigator:	Jose-Valentin Sera-Josef
IRB ID:	STUDY00007025
Funding:	None, None
IND, IDE, or HDE:	None
Documents Reviewed:	• Demographics Survey.pdf, Category: Survey / Questionnaire; • haptic_confirmation_email.docx, Category: Recruitment Materials; • Study 7025 Haptic_Recruitment_Email IRB edits (1).docx, Category: Recruitment Materials; • Study 7025 Haptic_Study_Consent (2) IRB edits (2).pdf, Category: Consent Form; • Study 7025 Haptic_Study_Protocol (1) IRB edits.docx, Category: IRB Protocol; • User Survey, Category: Survey / Questionnaire;

The IRB approved the protocol on 9/3/2024. Continuing review is not required.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system. Guidance on submitting Modifications and a Continuing Review or Administrative Check-in is detailed in the manual. If continuing review is required and approval is not granted before the expiration date, approval of this protocol expires on that date.

To document consent, use the consent documents that were approved and stamped by the IRB. Go to the Documents tab to download them.

When you have completed your research, please submit a Study Closure request so that IRB records will be accurate.

If you have any questions, please contact the UCF IRB at 407-823-2901 or irb@ucf.edu. Please include your project title and IRB number in all correspondence with this office.

Sincerely,

Harry Wingfield
Designated Reviewer

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